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Design of a boat electric propulsion system based on solar energy

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1. Abstract

Existing boat market demands highlight the need to identify eco-friendly solutions which can compete with the actual fuel based propulsions and reduce the greenhouse effect in the earth and the noise produced in the sea. Today, sailboats are the main boat type in the market that can be equipped with solar panels. Other electric boat models also exist, however they have low speed specifications. Thus, the aim of this thesis is propose an electric propulsion system equipped with solar panels that can compete with fuel-based boats in terms of speed. This electric propulsion system pretends to fulfil one of the weaknesses of the actual electric boat market, where (equipped with solar panels supplying the propulsion batteries) only some sailboats and low speed motorboats are offered. To do so, the different main components (i.e the motor, the batteries and the solar panels) have been studied and chosen. In addition, a components connection scheme has been proposed.

Besides of the motor and the batteries, the solution consists of a hardtop structure with solar panels placed on the roof in order to increase the available area to place the solar panels. To verify performance conditions, the hardtop design has been tested by FEM simulation (using ANSYS Workbench and Fluent) in different conditions (solar panels weight, snow conditions and wind conditions). In addition, with the aim to increase the vision factor between the sun and the solar panels installed in the roof of the hardtop, a solar panels orientation system has also been conceptually designed.

In addition, with a few modifications in the hardtop structure the proposed electric propulsion system can be installed in any boat of an approximate range from 4,5 meters to 6,5 meters. Results indicate that weight of the designed propulsion system is higher than a conventional fuel propulsion system. However, the difference is not significant and it could be assumed by the hull of the boat. In the future, it is of interest to further develop the solar panels orientation system, realize an own design of the components and to analyse in deeper detail the adaptability of the proposed propulsion system to other boat models.

SUMMARY

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3. Preface

Cars, motorbikes, boats, mechanisms and engineering in general has fascinated me since I was about five years old, at this time I used to play several hours with little cars. Becoming an engineer has been one of the dreams of my life. When I was at school and my parents bought my first bike in a few weeks I have had completely dismantled, and the same thing happened a few years later when I bought my first motorbike.

On the other hand, one of the passions of my life is boat fishing. For a fisherman taking care of the sea and respect the environment of the species is a very important matter so designing an electric boat was a motivating and an ambitious challenge for me.

4. Introduction

Nowadays, contamination in general is an important problem for our society. One of the most concerning issues is the greenhouse effect and as a consequence the global warming. One of the causes of the accelerated global warming is the emission of too much carbon dioxide (CO_2) by combustion motors to the air.

Every day, we are getting used to see more electric vehicles in the streets. But this is not occurring (still) in the boat industry. The potential benefits in this industry are as good as in car industry or better. Electric boats are an ecological-friendly alternative to the typical fuel-based propulsion system and are able to reduce the air pollution and practically eliminate the noise caused by fuel motors.

4.1. Project objectives and scope

With the aim to reduce the emissions produced by the fuel motors and also exploit the potential of renewable energy in boat industry, this project aims to propose an electrical propulsion system equipped with solar panels. Then, to understand and define all the components and connections is another of the main objectives.

Therefore, the design of a hardtop equipped with solar panels and the study of its adequate inclination to provide the propulsion boat system with clean energy has been in focus. In addition, an existing boat model equipped with the designed hardtop is explored as basis to explore the feasibility to develop new boat designs and prototypes.

During all this project, the intention has always been, to design a propulsion system as more adaptive as possible. That means that requires few changes to the hardtop structure design in order to be used in different boat types and sizes.

The scope of this project involves different tasks to accomplish the above-mentioned objective. These are:

- Boat hull propulsion electrification
- Study and selection of electric propulsion components (motor with control incorporated and batteries).
- Set the adequate electrical network connections between components.
- Study and selection of solar panels.
- Detailed design of the hardtop structure and FEM analysis.
- Conceptual design of an inclination system for the solar panels (hardtop).

4.2. Industrial motivation

Besides the explained ecological benefits (for instance the reduction of the CO_2 emissions), an electric system like the proposed in this thesis can also be very interesting for the actual industry and market.

Actually, with the constant evolution and changes of the electric motors and especially of the batteries, the boat industry is changing and day after day is bringing all these technologies to the market. Some recreational electric boat models are currently offered such as commercial sailboats which incorporate technologies like the hydro generation and solar panels. Most of the existing electric boat models (that also exploit the sun energy) are sailboats or have low speed specifications.

Thus, based on the recent market demands on new technological and renewable propulsion systems, the proposed solution could have a great demand and attract many customers.

5. State of the art

5.1. Basic boat definitions

Generally, boats consist of different parts. Fig. 1 (a) and Fig. 1 (b) indicates the most important ones based on a top and side view of a representative boat respectively. These parts are [1]:

- Stern: It is the rear part of a boat. In the stern there is the transom, the transom is the stern cross-section of a boat (see number 1 in Figure 1 (a)).
- Bow: It is the forward part of the hull of a boat. The bow is designed to reduce the resistance of the hull cutting through water and should be tall enough to prevent the entrance of water in the boat (see number 2 in Figure 1(a)).
- Starboard: It is the right side of the boat (when you are seated and looking forward) (see number 3 in Figure 1 (a)).
- Port: It is the left side of the boat (when you are seated and looking forward) (see number 4 in Figure 1 (a)).
- Waterline: It is the line painted on the hull, at which the boat sits in the water when it is properly loaded with equipment and passengers (see number 1 in Figure 1 (b)).
- Draft: It is the depth of water that is needed for the boat to float unobstructedly. It is measured as the distance between the waterline and the lowest point of the boat (see number 2 in Figure 1 (a)).
- Freeboard: It is the distance from the waterline and the lowest deck level (see number 3 in Figure 1 (a)).

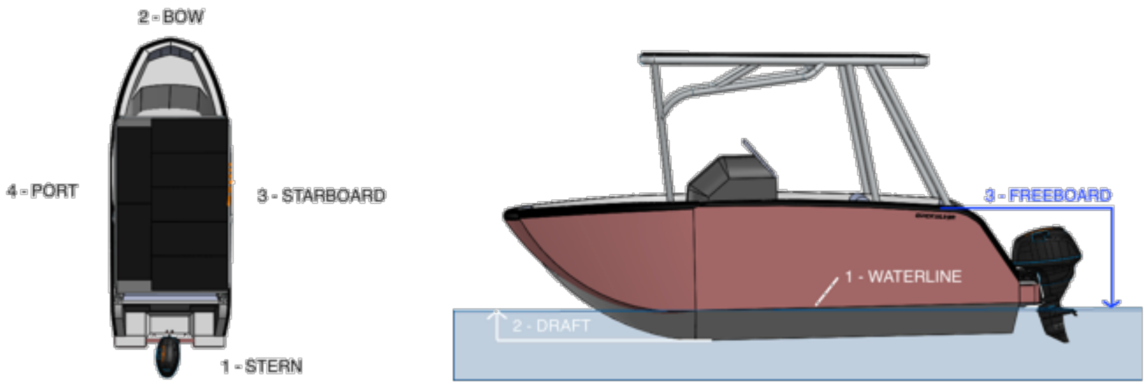

***Fig. 1 (a)** Superior view and **(b)** Lateral view*

5.2. Boats evolution

The oldest discovered boat is a 3 meters long Pesse Canoe. Carbon dating indicates that the boat was constructed during the Mesolithic period. But the first (considered) sailing boats were the Egyptian reed boats dated of (4000 BC).

Fig. 2 *Pesse Canoe*

Around 2500 BC, ancient Egyptians began to build wooden boats. These boats were able to resist sailing across the oceans. From about 1000 years after until about 300 BC, the Phoenicians constructed the galley (Fig. 3) The galley was a ship propelled mainly by rowing but it also had sails. The galley characteristics made these boats good in independently of winds and currents.

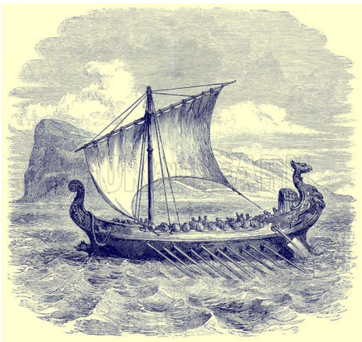

Fig. 3 *Galley*

Years ago (1000 AD), the Vikings started to build longboats, Vikings ships were narrow and long and allowed them travelling across the rivers and across the sea. Only 100 years later the Chinese began to use boats that they called Junks. Junks were used as transporting and fighting ships. Later in 1450 AC, wooden ships with two or three masts began to be used during several centuries. Wooden ships (as Junks) were used as transporting and battle ships.

Fig. 4 *Wooden ship*

In 1819, the first ships that were propelled by using steam began to cross the Atlantic Ocean. A few years later in 1845, first iron ocean going liners began to appear.

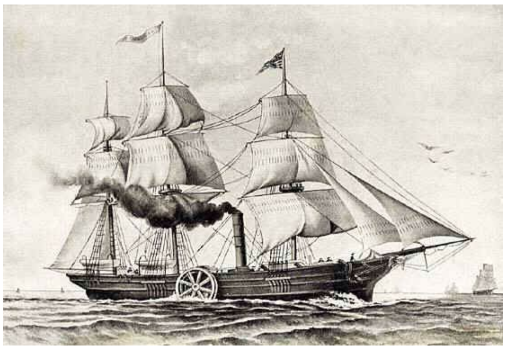

Fig. 5 *Steam propelled ship*

In 1910 began the conversion of the coal powered ships to diesel power and oil started to be used instead of steam. During the XX century, container ships began to be more used to transport cargo and passenger cruise ships started to take people on holidays. [2]

5.3. Current types of recreational boats

In the actuality boats, as all the technology, have changed. Along this point, are mentioned some of the current types of recreational boats. [3]

5.3.1. Recreational fishing boats

Fishing boats as the name suggests, are used for fishing activities. This type of boat is used on both salt and freshwater bodies. Fishing boats are characterized for qualities like the strength, the stability and the durability to resist in hard conditions across various kinds of waterways. Usually include features such a front bow, rod lockers and a trolling motor system.

Fig. 6 *Recreational fishing boat*

5.3.2. Bass Boats

A bass boat is a small boat with slim profiles designed principally for bass (or other fishes like perch or sunfish) fishing. These boats are usually used in freshwater such as lakes, rivers and streams. In addition, they have swivel chairs that gives the angler the freedom of casting to any position around the boat.

Bass boats commonly are propelled by an outboard motor and a trolling motor. The first one is utilized to move fast the boat, and the second one is used by the angler to approach to the fishing zones slowly and quietly. If both motors fail, this type of boats are small enough to move using a coat.

Fig. 7 *Bass boat*

5.3.3. Bowrider boats

The bow area of this boats is prepared to allow an spacious seating arrangement. A bowrider boat is usually sized between 5 meters and 11 meters. These boats are typically used for recreational activities like wake-boarding and swimming.

Bowrider boats are powered by many types of engines, depending on the size or the style of the boat. Some are designed to cruise more quietly and some are intended to be quite fast. The design and the geometries of the boat are most well suited to inland waterways and calm lakes rather than open oceans.

Fig. 8 *Bowrider boat*

5.3.4. Catamaran boats

A catamaran is a multi-hulled featuring two parallel hulls of the same size. The catamaran high beam gives a high stability to the embarkation compared with a mono-hull. Catamarans usually have less shallower draft and hull volume than a mono-hull sailboat. The two hulls are connected with a structure that ranges from a simple frame to a bridging structure incorporating a cabin or cargo space.

Catamarans could be small like little sailboats and large as navy ships and ferries. Depending on the use and the size, catamarans can be propelled by inboard, outboard motors or by sails.

Fig. 9 *Catamaran boat*

5.3.5. Cuddy cabin boats

These boats have a small shelter cabin and sometimes also with a small head. The presence of this small cabin allows a very useful storage in the boat which facilitates the navigation.

This type of boats is well-suited for activities like fishing, yachting, sailing and other water sports. Commonly cuddy cabin boats are built of fiberglass or aluminium. The length range goes from 4,75 meters to 8,5 meters.

Fig. 10 *Cuddy cabin boat*

5.3.6. Centre console boats

A centre console boat is a kind of single-decked open hull boat that the control console is placed in the middle of the embarkation. Some variants have a little cabin situated under the bow. This cabin as in cuddy cabin boats is very useful for storing things and sometimes hold small beds for sleeping. Consequently, of the hull deck distribution, the occupants of the boat can walk around the boat from bow to stern easily.

These boats are fast boats usually propelled by an outboard motor. As consequence of this type of boat characteristics, these boats are very used for spinning fishing.

Fig. 11 *Centre console boat*

5.3.7. Recreational trawler boat

They can also be called cruising trawlers or yacht trawlers and are joy boats. Recreational trawlers resemble fishing trawlers. Trawlers are slow boats with low fuel consumptions, typically they have a cruise speed of 7-8 knots.

Trawlers range of length is from 11 meters to 18 meters or more. Most are prepared for long cruises and can host from two to eight persons for many days. A trawler boat can be used as permanent home.

Fig. 12 *Recreational trawler boat*

5.3.8. Motor yacht boats

Yachts are marine vessels used for sports and enjoyment. This kind of boats length starts in 10 meters and they can reach over 50 meters. In the latter case, they are called megayacht. Usually they are the most expensive boats and they are equipped full of luxuries. As the recreational trawlers are prepared to host people and are perfect to cruise large distances.

Usually are propelled by one or two diesel or gasoline inboard motors. Given that these motors have lots of horsepower these boats are swift but also have high consumptions and have a costly maintenance.

Fig. 13 *Motor yacht boat*

5.4. Existing boat engines

5.4.1. Outboards (general way)

An outboard motor is a propulsion system for boats. These engines are designed to be fixed to the outside of the transom, in the stern (i.e. see number 1 in Fig. 1 (a)). They are the most common motor type used for propelling small boats. One of the advantages of the outboard motors is that they can be removed easier than an inboard motor, consequently outboard motors are more accessible and easier to repair.

While the boat (propelled by an outboard) is navigating through shallow waters the engine can be tilted up. Depending on the model the elevation can be realized manually or electronically. This kind of motor is prepared to pivot over their mounting, thus the direction is controlled with thrust.

As it can be observed in (Fig. 14) the superior part of an outboard is called powerhead, and the intermediate part is called midsection.

The general parts of an outboard are:

- **Engine:** It is the responsible of power the system. Usually are 2 stroke and 4 stroke motors.
- **Mounting bracked**: Is where the outboard is fixed to the boat.
- **Water intake:** Is the water supply for the cooling system.
- **Exhaust:** It conveys burnt gases from the engine.
- **Propeller**: It transmits rotational motion into thrust.
- **Skeg:** It acts as a rudder when engine is not running.
- **Anti-ventilation plate:** It reduces the cavitation phenomenon.

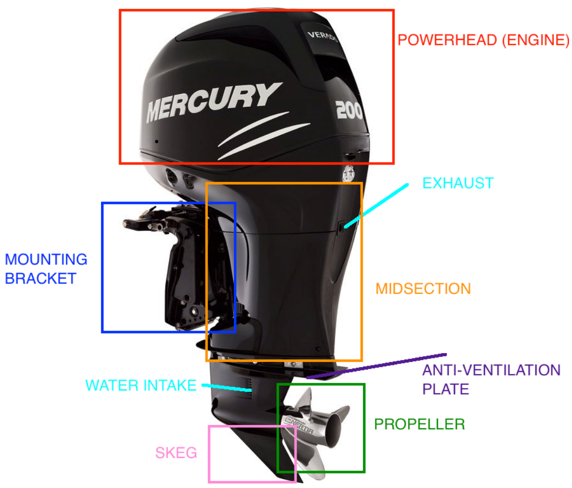

Fig. 14 *Outboard parts*

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Four of the most known outboard brands are: Yamaha (japanese), Mercury (american), Susuki (japanese) and Honda (japanese). These brands offer different outboards models that are ranged from 2,5 hp to 425 hp.

Fig. 15 *Principal outboard brands logos*

5.4.2. Principal boat electric motors

Actually, some (outboard, inboard and pod) electric motors for boats are offered by different marine brands in the marked.

In summary, the principal electric motors brands are:

- **Elco:** Elco offers 100% electric and hybrid motors. Electric outboards and inboards are offered from 6hp to 100hp.

Fig. 16 *Elco Logo*

- **Oceanvolt**: Oceanvolt offers 48V electric pod and inboard motors. They also offer Lithium ion batteries and generators.

Fig. 17 *Oceanvolt Logo*

- **Aquawatt:** They offer 100% electric inboard and outboard motors with a power from 20hp to 70hp.

Fig. 18 *Aquawatt Logo*

- **Torqeedo:** Torqeedo is the market leader and offers inboards, outboards (full electric motors) and hybrid drive systems.

Fig. 19 *Torqeedo Logo*

5.4.3. Existing electric boats and propulsion electric systems (with solar panels)

Nowadays (obviously), there are many electrical propelled boat models. But when we take a look into the electric boat market, we can see that it is not easy to find electric models that incorporate solar panels to provide energy to the propulsion batteries.

The intention of this chapter is to show the principal (similar) commercial options that are offered in the market actually.

- Aquawatt 550:

The aquawatt 550 is an electric boat with a length of 5,5 meters with a sustainability of 4 persons. It is equipped with solar panels and is offered with two motor versions. With the 1600 Watts version the boat maximum speed is 6 knots and with the 800 Watts version it is 4,7 knots.

With an optimum sunshine, it can drive six hours continuously at 5,5 knots and ten hours at 4 knots. [4]

Fig. 20 *Aquawatt 550*

- Oceanvolt propulsion system for monohull and multihull:

Oceanvolt systems are engineered to operate in 48V (pod motors), these systems range and recharging are achieved either through hydro generation or through solar energy which can enable constant long-range cruising. [5]

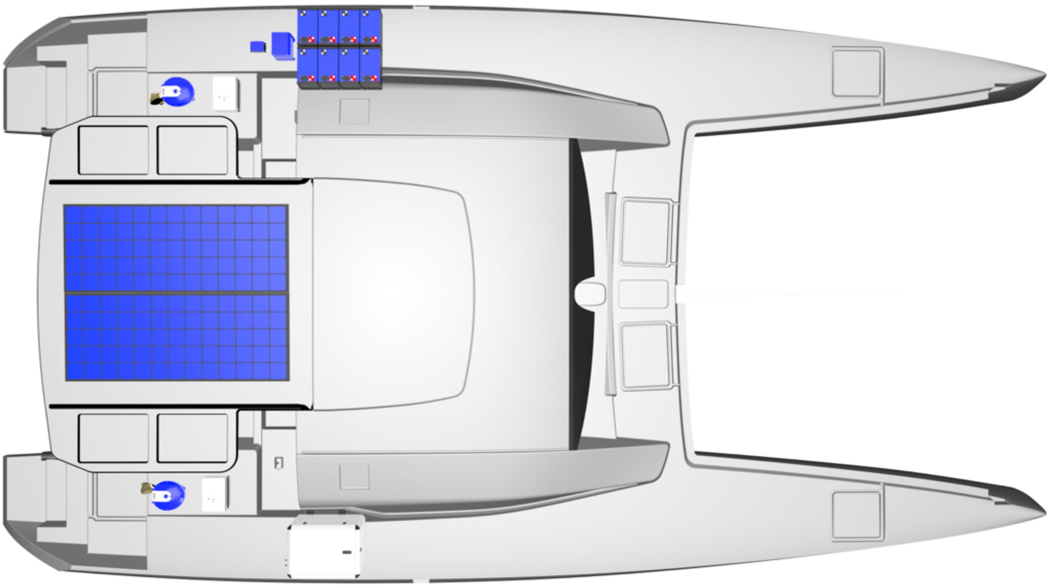


Fig. 21 *Oceanvolt multihull propulsion system*

This Oceanvolt propulsion system is equipped in some existing models like:

- **DNA G4:** which is a daysailing catamaran. It has a length of 12,14 meters and is equipped with the 8 kW Oceanvolt SD8 electric saildrive motor which is retractable.

Fig. 22 *DNA G4*

- **VOYAGE 480:** the VOYAGE 480 is a catamaran with a waterline length of 13,56 meters propelled by two Oceanvolt SD15 electric sail drive motors
  The 48 V electric motors are provided by a bank of high capacity (16 kWh) Lithium-Ion batteries.

Fig. 23 *VOYAGE 480*

6. Basic idea and specifications

6.1. Basic components and connections

As it has been explained before, the main purpose of this project is the electric propulsion system (the more adaptable as possible) of a boat taking as basis a Quicksilver Activ 505. It has been chosen a concrete model specially for designing the hardtop. This Quicksilver Activ model has been selected because it is a popular boat model bought in the market and therefore it accomplishes the desired dimensions and specifications but another similar boat model could have been chosen.

As the most of the models offered actually in the market, this model is only offered with different fuel based motor options. In a general way, the basic components of a fuel based propulsion are the engine and the fuel tank.

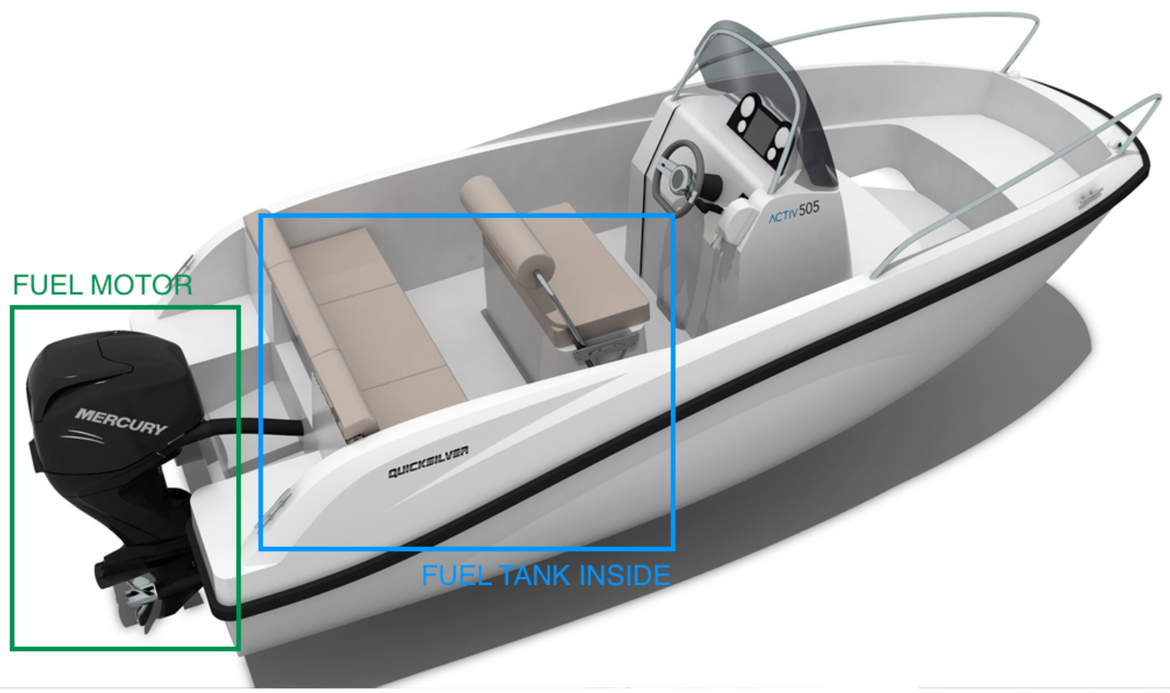


Fig. 24 *Basic fuel propulsion components*

Along general lines, in this project it has been supposed that these components have been removed from the hull and then the electrical solution have been proposed.

Thus, taking the hull of the boat all the different basic boat propulsion components (motor, batteries and solar panels) have been chosen. Then, a proposal of the connections between these components has been done. Moreover, a hardtop to position the solar panels on the top has been designed.

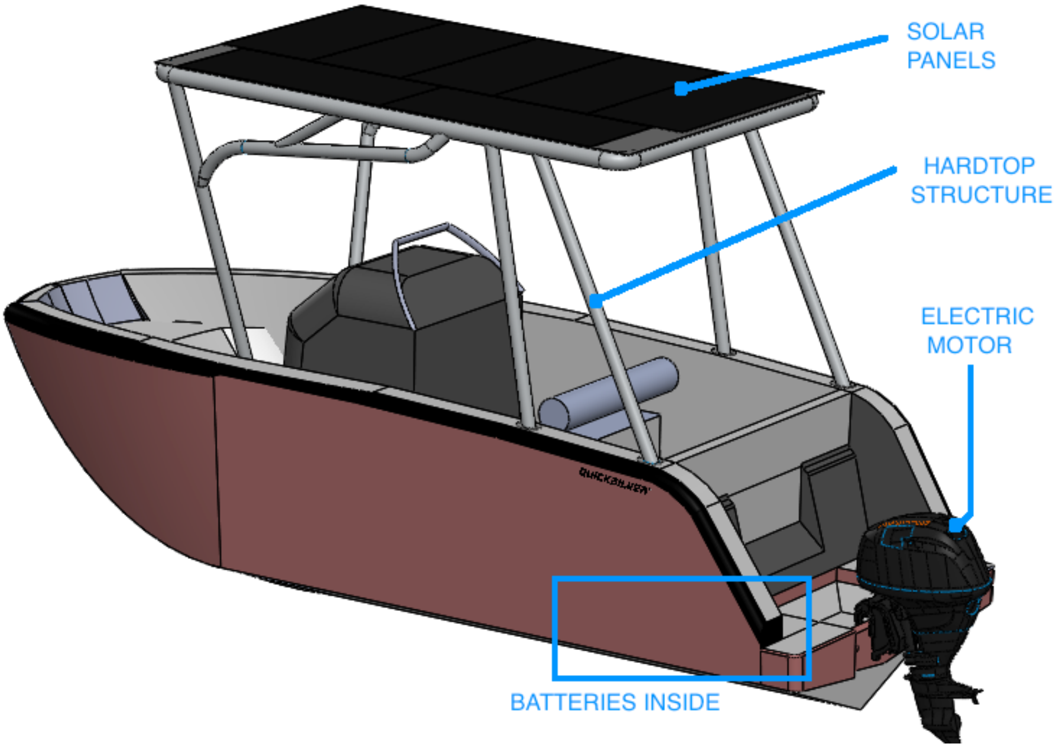


Fig. 25 *General parts of an electric propulsion*

6.2. Required system conditions

The design and the boat components depend on the conditions that the propulsion system needs to fulfil. These are explained below:

- **Adaptability specifications:** the system propulsion specification needs to allow a design that can be applicable, that is with little design modifications as possible, in different types of boats with an approximated length ranging from 4 m to 6 m such as centre console, bass, bowrider or catamaran boats.

- **Competitive specifications:** given the typical uses of this kind of boats, the system has to give at less a maximum speed approximated of 14 knots. In addition, in order to design a high efficiency propulsion system, the weight of the whole electric system has to be similar to the fuel based system.

7. Basic boat propulsion system components

To design an electrical boat propulsion that results in high efficiency, the weight and volume of all the parts and pieces included to such system are of high importance. In this thesis, 3 main components are considered to build the electrical propulsion system. These are:

- The motor.
- The batteries.
- The solar panels.

Thus, in this chapter these components have been analysed and chosen.

7.1. Motor:

The electric motor chosen to be placed into the energy propulsion system proposed in this thesis is a Torqeedo motor. Torqeedo is a German marine electric motor and marine batteries manufacturer that sells its products around the world. Torqeedo was founded in 2005 by Christoph Ballin and Friedrich Böbel in Starnberg. [6]

All Torqeedo motor models are always synchronous. In this kind of motors, the ratio of the motor speed to the frequency of supply voltage is constant. Synchronous motors are torque controlled which means that they consume the necessary current to transfer the necessary power to the desired motor speed.

In addition, Torqeedo motors are electronically commutated motors. This means that the alternating field is generated by the motor via electric switching. Thanks to this technology no brush loss is produced and the motors are maintenance-free. Moreover, the magnetic field is generated by permanent-magnets. Thus, any loss of performance due to the excitation coil is avoided. [7]

7.1.1. Motor sizing analysis:

To realize the motor sizing analysis a *Quicksilver Activ 505* has been taken as basis. To choose the horsepower different fuel versions are analysed.

Since *Quicksilver* boats only work with the fuel engines brand *Mercury marine*, the analysis below is carried out considering some *Mercury engines*. For the *Quicksilver Activ 505* model the maximum power allowed is of 100 hp. However, different *Quicksilver Activ 505* models are offered: model equipped with the Mercury 40 Four stroke (40 hp), the Mercury 40 Orion (40 hp), the Mercury 50 Four stroke (50 hp), the Mercury 60 Four stroke (60), the Mercury 60 Bigfoot (60 hp), the Mercury 75 Optimax (75 hp), Mercury 80 Four stroke (80 hp) and the

Mercury 90 Optimax (90 hp). In the internet page (touron-nautica.com) have tested the above-mentioned motors. [8]

The results of these speed tests are shown in the following Table 1:

ENGINE	*HP (kW)*	*CRUISE SPEED (knots)*	*MAXIMUM SPEED (knots)*
Mercury 40 Four stroke	40 (29,83)	15,9	23,1
Mercury 40 Orion	40 (29,83)	16,5	22,9
Mercury 50 Four stroke	50 (37,285)	17,9	25,8
Mercury 60 Four stroke	60 (44,742)	18,5	27,9
Mercury 60 Bigfoot	60 (44,742)	20,2	28,2
Mercury 75 Optimax	75 (52,2)	23,4	30,2
Mercury 80 Four stroke	80 (59,65)	23,3	30,5
Mercury 90 Optimax	90 (67,11)	24,9	36,1

Table 1 *Speed tests results*

Results from table 1 shows that the motor power range has to be fenced from about 40 hp (29,83 kW) to 90-100 hp (67,11 kW to 74,57 kW). Therefore, in order to be competitive, the energy boat system to be designed requires a motor of these characteristics in order to compete with the fuel propelled models.

In Torqeedo offer four different electric outboard models. These are: Ultralight (1 hp), Travel (1,5 hp and 3 hp), Cruise (5 hp and 20 hp) and lastly, Deep Blue (40 hp and 80 hp). In order to fulfil the power range required (I.e. from 40 hp to 90-100hp), Deep Blue is chosen as part of the electric system energy boat propulsion.

In order to identify which of the two electric motor versions of Deep Blue motor (40 hp and 80hp) is more adequate for the system to develop, the motor consumption is analysed. Speed has also been considered. As it is showed in the previous table 1, the maximum speed by the analogous fuel motors is of 22,9 knots and 30,5 knots respectively. This is an acceptable speed for the conditions in which the open boats, such as the *Quicksilver Activ 505,* have to be used. By comparing the input power required by the two motors (See table 2), the chosen motor is the *Torqeedo Deep Blue 40* since it consumes 33% less compared with the 80hp version.

ENGINE	*INPUT POWER (KW)*
Torqeedo Deep Blue 40 (outboard)	41
Torqeedo Deep Blue 80 (outboard)	61

Table 2 *Deep Blue models input power*

SPECIFICATIONS	*VALUE*
INPUT POWER	30 (KW)
PROPULSIVE POWER	16.2 (KW)
COMPARABLE GAS OUTBOARDS	40 (HP)
NOMINAL VOLTAGE	345 (V)
MASS	139 (Kg)

Table 3 *Torqeedo Deep Blue 40 specifications*

7.1.2. Deep Blue 40 part analysis:

As it can be observed in Fig.26, there are four principal parts that can be distinguished: [9]

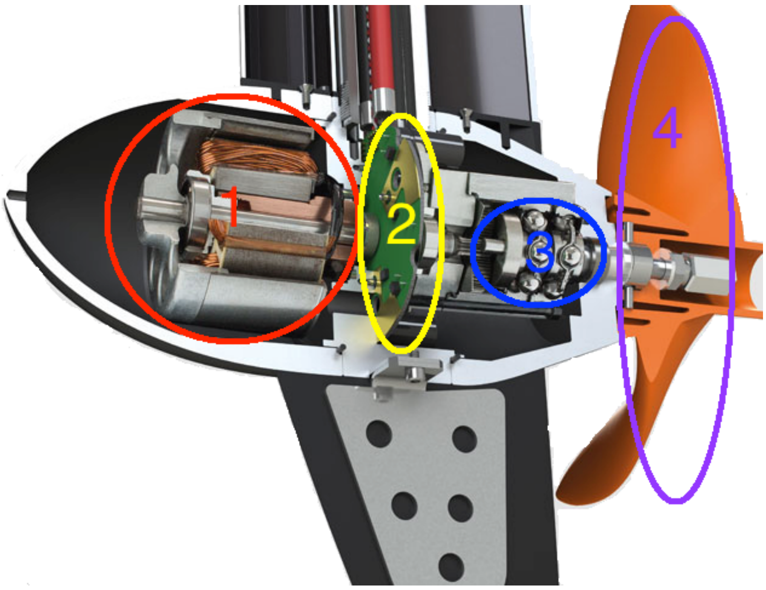


Fig. 26 *Torqeedo Deep Blue parts*

Brushless external rotor motors with rare-earth magnets (number 1 in Fig.26): Torqeedo use external rotors, with the stator and the coils located in the interior, allowing magnets to rotate. This design produces a better torque given that the field in which the torque is produced is more external. This torque (compared with a conventional motor) is up to twice times greater. Due to there is more space into the interior of the motor, there are the double of magnets. Moreover, in Torqeedo electric motors rare-earth magnets are used. These rare-earth magnets have about five or six times the strength of a regular magnet.

Tailor-made power electronics (number 2 in Fig.26): To switch on an electric motor is necessary an extra magnetic field. In traditional electric motors this necessary magnetic field is generally produced by using sliding contacts or brushes, however in Torqeedo motors this magnetic field is produced without any contacts. This field is created via contactless electronic digital switching. It switches the current flow through the coils 35.000 times per second. As a result of brushless the friction is reduced and evidently the efficiency increases. It is also necessary to add, that Torqeedo power electronics are speed-controlled, enabling perfect slow manoeuvring.

High quality gearbox (number 3 in Fig.26): Due to the propellers, high efficiency is produced when the torque is maximum and the rotational speed is low, Torqeedo always use gears for transmissions. Planetary gears are typically used.

Propeller design from commercial shipbuilding (number 4 in Fig.26): The most efficient propellers are which ones that have a large diameter, a high pitch and a low rotational speed. The efficiency in a propeller that needs a high rotational speed decreases because of the cavitation. Thus, motors with high torque can work efficient propellers. But having a high torque is not the only factor that increases the efficiency of a propeller, apart from this, there should be as few differences as possible between the highest and the lowest points on the motor's torque curve.

7.1.3. Motor electricity consumption and autonomous speed:

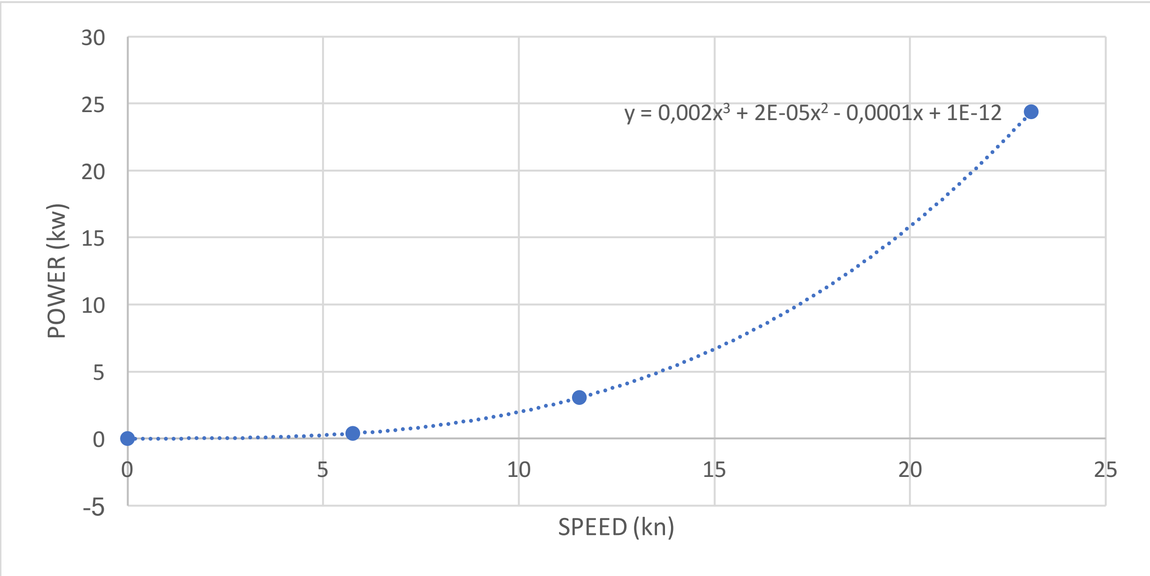
For a boat making way through the water, the required propulsive power increases in proportion to the cube of the speed. This means that if you want to double the speed, eight times as much power is needed. Using this premise, the instantaneous power has been calculated in four different speeds as shown in table 3.

The instantaneous power at the maximum speed (23,1 kn), has been calculated with the range data given by Torqeedo. In Torqeedo say that the maximum running time (full throttle), with a battery with a capacity of 30 kWh, is 1 hour 15 minutes. Thus, with this information as starting point and with the explained premise, the second and the third points of the table 4 have been calculated.

	BOAT SPEED (knots)	*INSTANTANEOUS POWER (kw)*
1	23,1	24,4
2	11,55	3,05
3	5,77	0,38
4	0	0

Table 4 *Speed vs Power points*

When these points are plotted we can obtain the graphic 1. The Y axis of the graphic represents the instantaneous power and the X axis represents the speed. Also, the regression line and equation of the points have been found.



Graphic 1 *Speed (kn) vs Power (kw)*

$$Power\ (kw) = 0{,}002 \cdot (speed)^3 + 2 \cdot 10^{-5} \cdot (speed)^2 - 0{,}0001 \cdot (speed) + 10^{-12}$$

Equation 1 *Power consumption depending on the boat speed*

When the obtained equation is analysed (Equation 1), it can be observed that the most significant coefficient is the (0,002·speed^3). This gives coherence to the equation because it represents the viscous friction. The other coefficients are not significant. But in this case the (0,0001·speed) factor could appear as consequence of the dry friction.

Given the power offered by the solar panels, Equation 1 can be used to obtain the autonomous speed for the open boat in focus. (see Equation 2).

Considering the solar panels chosen (see section 7.3), the maximum input power given by the: seven solar modules is 840 W (120 W each one,). In fact, this solar panels will not have a 100% efficiency. Thus, the calculus has been done with the maximum efficiency (100 %) and with a more real efficiency (80 %). Obviously, the weather of the zone where the boat is sailing affects to the efficiency. Considering a 100% solar panels efficiency, the maximum autonomous speed is of 7,48 knots (equation 2). Instead, if a solar panels efficiency of 80% is considered, the real autonomous speed corresponds to 6,95 knots (equation 3).

$$Power = 0{,}002 \cdot (speed)^3 + 2 \cdot 10^{-5} \cdot (speed)^2 - 0{,}0001 \cdot (speed) + 10^{-12} = (7 \cdot 0{,}120) \cdot 1 = 0{,}840\ (kW) \rightarrow speed = 7{,}48\ (kn)$$

Equation 2 *Autonomous speed calculation with 100% of solar panels efficiency*

$$Power = 0{,}002 \cdot (speed)^3 + 2 \cdot 10^{-5} \cdot (speed)^2 - 0{,}0001 \cdot (speed) + 10^{-12} = (7 \cdot 0{,}120) \cdot 0{,}8 = 0{,}672\ (kW) \rightarrow speed = 6{,}95\ (kn)$$

Equation 3 *Autonomous speed calculation with 80% of solar panels efficiency*

7.1.4. Throttle controller

As its name indicates, the principal function of the throttle controller is to control the speed and the direction of rotation of the propeller. In this case, the throttle controller is a high-quality potentiometer to read changes in the lever position. Depending on the position of the lever, the intentions of the driver (speed up, hold the same speed or slow down) are known and the controller adjusts the power of the electric motor to increase the speed or to reduce it.

In this case, a top mounted Torqeedo throttle controller (Fig. 27) has been selected.

Fig. 27 *Torqeedo throttle controller*

7.2. Batteries

As the solar panels, the batteries are one of the most important parts of the design. The batteries must be able to work several hours continuously. In general, there are two kinds of batteries depending on if they can be charged or not. Evidently, in the proposed electric propulsion system a rechargeable battery should be used.

There are different types of rechargeable batteries but lead acid batteries, NiCd batteries and Lithium-Ion batteries are the most remarkable.

7.2.1. Kinds of batteries

- **Lead acid based batteries**

The lead acid battery is the oldest type of rechargeable battery and it was invented in 1849. Despite having a very low energy-to-weight and a low energy-to-volume, its hability to supply high surge currents means that the cells have a relatively large power-to-weight ratio. Lead acid batteries are habitually used in the automotive and naval industry to provide the necessary energy to the starter motors. There are three basic types of lead acid batteries: flooded batteries, absorbed glass mat batteries (AGM) and gel batteries. The advantages and disadvantages of the lead acid batteries are illustrated in the table below: [10]

Advantages	Disadvantages
-Are inexpensive and simple to manufacture. -Low self-discharge. -high specific power. -Good low and high temperature performance	-Low specific energy. -Slow charge. -Must be stored in charged condition to prevent sulfation. -Limited cycle life. -Flooded type requires watering. -Transportation restrictions on the flooded type. -Not environmentally friendly.

Table 5 *Advantages vs disadvantages (Lead based batteries)*

- **Nickel-Cadmium (NiCd) based batteries**

On the other hand, NiCd batteries were invented in 1899 and they use nickel oxide hydroxide and metallic cadmium as electrodes. These batteries are more complex to charge than Lithium-Ion and lead acid. Nickel-based batteries charge with constant current but the voltage is allowed to rise freely. For many years, NiCd was the preferred battery choice for two-way radios, emergency medical equipment, professional video cameras. The advantages and disadvantages of the NiCd batteries are illustrated in the table below: [11]

Advantages	Disadvantages
-Rugged, high cycle count with proper maintenance. -It is the only kind of battery that can be ultra-fast charged with little stress. -Good load performance (forgiving if abused). -Long "shelf" life (it can be stored in a discharged state). -Good low-temperature performance. -Economically prized.	-Relatively low specific energy (if we compare with the newer systems). -It needs periodically full discharges. -Cadmium is a toxic metal.

***Table 6** Advantages vs disadvantages (NiCd based batteries)*

- **Lithium-Ion batteries**

Lithium-ion batteries general parts are a cathode (positive electrode), an anode (negative electrode) and electrolyte (as conductor). During discharge the ions flow from the anode to the cathode through the electrolyte and separator. In the case of charge, it reverses the direction and the ions flow from the cathode to the anode (see Fig. 28).

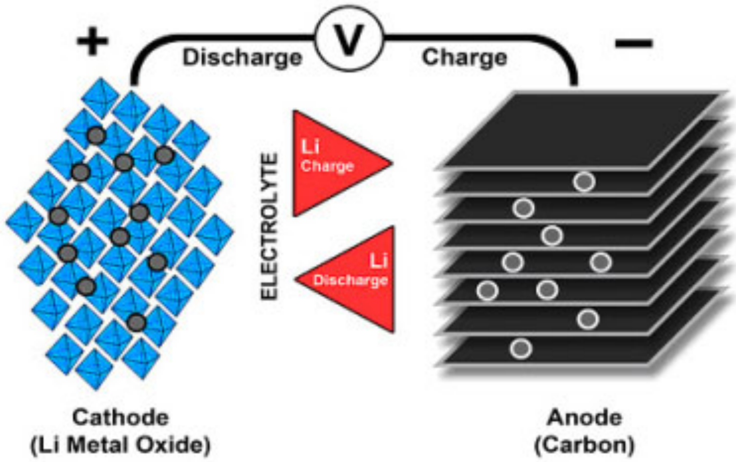
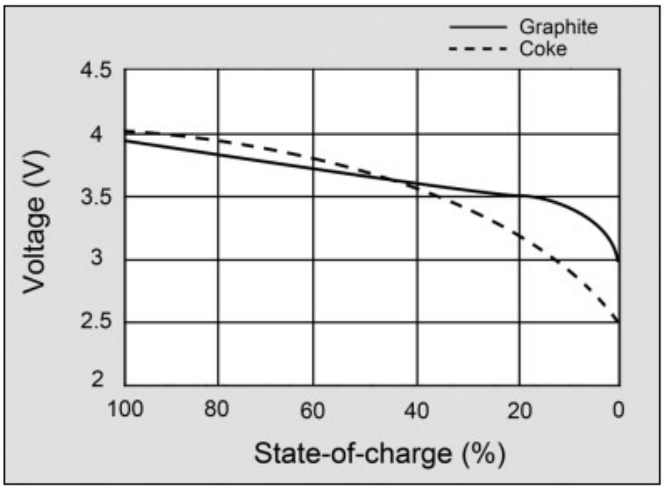


Fig. 28 *Lithium-Ion batteries operating bases*

Usually the negative electrode of a lithium-ion cell is made from carbon and the positive electrode is typically made from a metal oxide.

Lithium is the lightest of all metals, it has the greatest electrochemical potential and provides the largest specific energy per weight. The key to the superior specific energy is the high cell voltage. The discharge curve (Graphic 2) offers an efficient utilization of the stored energy in a voltage spectrum from approximately 4 V/cell to 2,8 V/cell. [12]



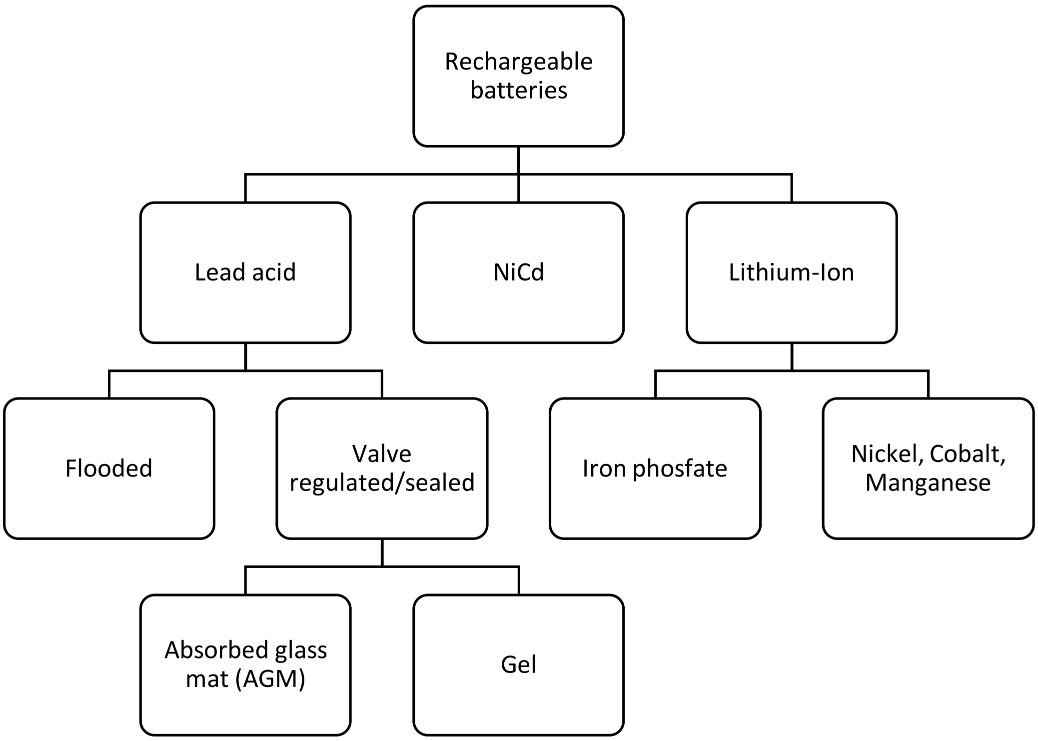
Graphic 2 *Voltage vs state-of-charge*

Given these exceptional qualities of the lithium-ion batteries, this kind of batteries are usually used in portable devices (like mobile phones), power tools (like sanders, saws or other equipment) and in electric vehicles. The advantages and disadvantages of the Li-on batteries are illustrated in the table below:

Advantages	Disadvantages
-Have a high specific energy and high load capabilities with power cells. -Long cycle and extend shelf-life. -Maintenance free. -Reasonably short charge times. -Low self-discharge.	-Requires a protection circuit to prevent thermal runaway if stressed. -Degrades at high temperature and when stored a high voltage.

***Table 7** Advantages vs disadvantages (Lithium-Ion batteries)*

7.2.2. Batteries summary



7.2.3. Battery technology in vehicle applications

Battery technology is often applied in the automotive industry. In fact, the applications of the rechargeable batteries in (electric or fuel-based) cars are typical and varied. In addition, one can see that the propulsion system of a car is similar (in many ways) to a boat propulsion system.

Different types of car propulsion system exist today. These are divided into: conventional, start and stop, micro-hybrid, hybrid and plug in and electric cars. Conventional cars only use the battery to turn on engine, typically use igniting (SLI) batteries which can give the necessary peak of energy. Start and stop is a system that automatically shuts down and restarts the internal combustion engine to reduce the motor emissions, the most common batteries in cars that incorporate this system are the enhanced flooded batteries (EFB) and the absorbed glass mat batteries (AGM). Then, hybrid and micro-hybrid cars are vehicles that are powered by a combustion motor and an electric motor working coordinately. Commonly, lithium-ion batteries are used in this propulsion systems. Lithium-ion batteries are also used by plug-in and electric cars. Electric cars are propelled only by an electric motor. High voltage batteries are typically used by electric cars. [13]

7.2.4. Battery choosing

From a conceptual perspective, it can be assumed that an electric boat is very similar to an electric car being the mode of application (ground/earth) the difference between such. Thus, based on the description of the batteries previously described and its application to electric cars, the most adequate battery for an electric boat is a high voltage lithium-Ion battery.

The most advanced li-ion car batteries have been compared in order to choose the battery brand that could best fit the electric boat propulsion system. Kia Soul EV battery is the battery model finally chosen due to its high capacity (30 kWh). Kia soul EV battery is formed by eight cell modules. Each cell module is made up of 14 or 10 cells and the battery consists of four modules of each kind connected together in series. This li-ion battery weights 274,5 kg. [14]

SPECIFICATIONS	*VALUE*
BATTERY TYPE	Lithium-Ion
NUMBER OF CELLS	192
NOMINAL VOLTAGE	375 (V)
CAPACITY	30 kWh
MASS	274.5 (Kg)

Table 8 *Chosen battery specifications*

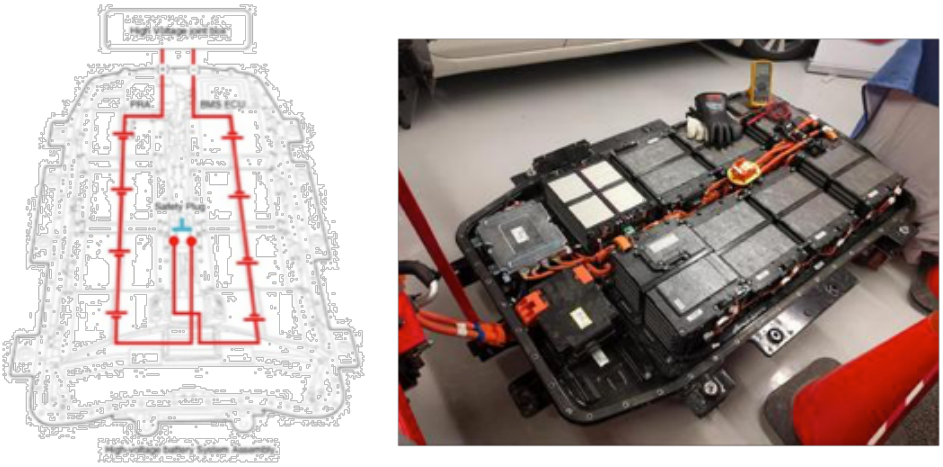


Fig. 29 (a) *battery scheme* ***(b)*** *Kia Soul EV battery*

7.3. Solar panels:

On average, every square meter of Earth's surface receives 164 watts of solar energy. This energy arrives on Earth as a mixture of light and heat. Light energy from the sun is used to generate energy through the photovoltaic effect. A solar panel is a collection of solar cells, the majority of the solar panels use crystalline silicon cells or thin-film cells. The more light that hits these cells, the more electricity them produce. As a curiosity, some special solar modules include light concentrators to focus the light onto smaller cells.

All the photovoltaic module elements have to be prepared to resist mechanical damage and moisture. For example, the most of modules use MC4 connectors type. MC4 connectors are single-contact electrical connectors.

Electricity from a range of frequencies of light can be produced by the photovoltaic modules, but usually the entire solar range cannot be covered (specially, ultraviolet, infrared and low or diffused light). Hence, much of the sunlight energy is wasted by solar panels and they can deliver higher efficiencies with monochromatic light. [15]

A solar cell is a small disc of a semiconductor attached with the other ones by wire to a circuit. If we analyse nearly the interior structure of a solar cell, we can find (as is showed in the Fig. 30) a kind of sandwich of n-type and p-type semiconductor, when light hits the surface of the solar cell the photons carry their energy down through the n-type layer to the p-type layer. When this energy arrives to the p-type layer electrons take it to jump into the upper layer and escape out into the circuit. [16]

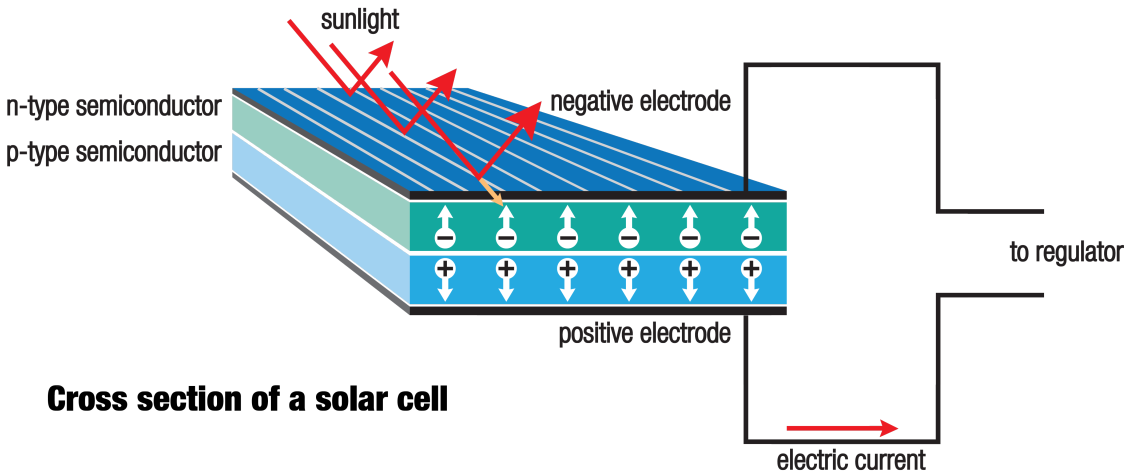


Fig. 30 *Solar cell functioning*

In this case, for its properties and specially its lightweight we have chosen to mount a high efficiency flexible solar panel. These modules are prepared to be mounted in boats so they are prepared to resist seawater corrosion conditions. The properties of these modules are shown in the table below (Table 9). These modules combine a lightweight (2,34 Kg per module) and a high efficiency (cells efficiency is 22,6%). Thus, each solar panel could deliver a maximum power of 120W. The dimensions of each solar module are 540 (mm) x 1200 (mm) x 3 (mm) and has 36 USA A grade SunPower solar cells.

SOLAR PANEL MODULE SPECIFICATIONS (per module)	*VALUE*
MAXIMUM POWER	120 (W)
MAXIMUM VOLTAGE	20.88 (V)
MAXIMUM AMPERAGE	5.97 (A)
CELL EFFICIENCY	22,60 (%)
NUMBER OF CELLS	36
MASS	2.34 (Kg)
DIMENSIONS	540x1200x3 (mm)

Table 9 *Chosen solar panels specifications*

As shown in (Fig. 30) seven solar panels can be placed to the boat considering a hardtop surface of 3,51 m^2.

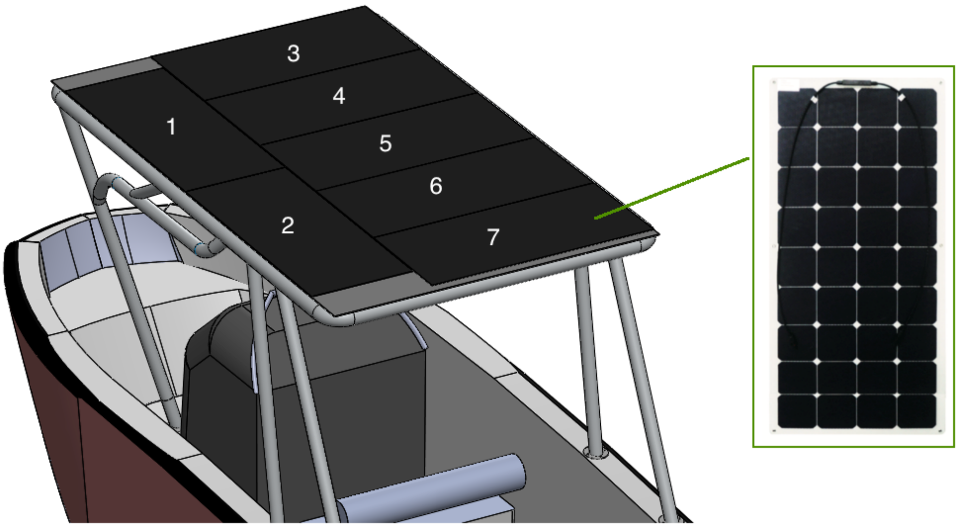


***Fig. 31** Hardtop equipped with the solar panels*

7.4. Weight comparison between fuel and electric propulsion system

The aim of this section is compare the weight of the fuel propulsion components with the weight of the proposed electric propulsion system. It has been compared to prove that the weight difference could not cause navigating problems or even sink the boat.

7.4.1. Main fuel propulsion components weight

- Fuel outboard: On average the fuel outboards that are capable to offer similar benefits and are allowed for this kind of boats weigh approximately 1962 N (200 kg).
- Fuel tank: Taking a look into the different boat models with the desired specifications, it has been observed that the 60-70 litters tanks are the typical used in these cases. Thus, 60-70 litters of gasoline weighs 400-467 N (40,70-47,6 kg) plus approximately the weight of the own tank 196,2 N (20 kg).
- So, the **whole fuel propulsion components weigh** is approximately **2629 N (268 kg)**

7.4.2. Main electric propulsion components weight

- Electric outboard: The proposed electric motor (as it is explained in section 6.1) weighs 1363,6 N (139 kg).
- Batteries: The proposed batteries (as it is explained in section 6.2) weighs 2688 N (274 kg).
- Solar panels: Given that the weight of each solar panel is 22,95 N (2,34 kg) and the

propulsion system is equipped with seven solar panels, the total weight of the solar panels is 160,68 N (16,38 kg).

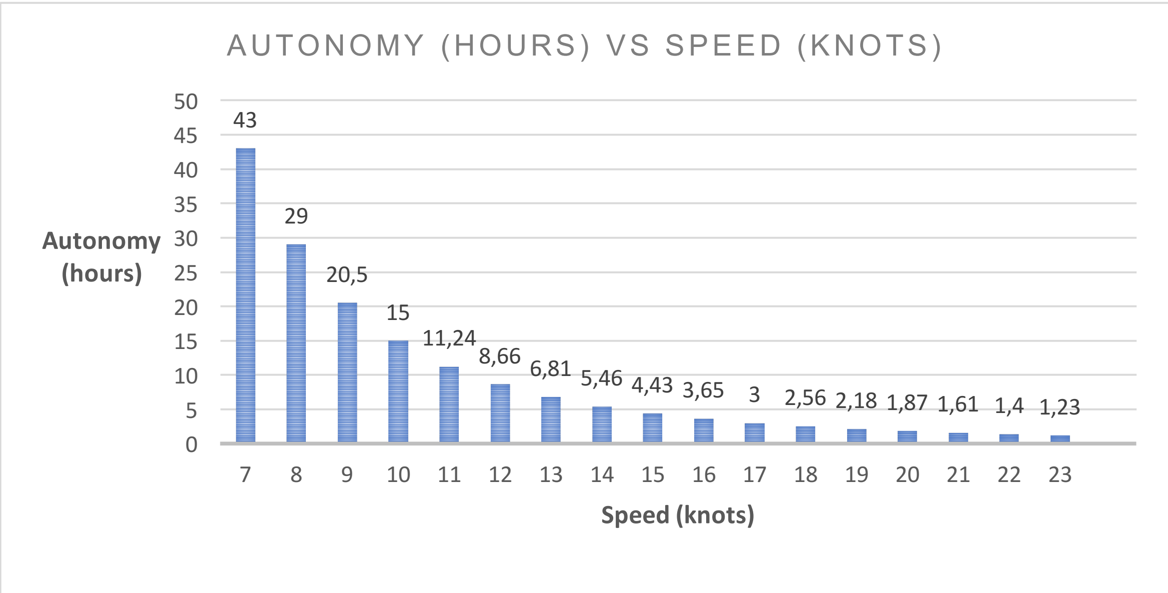
- As a result, the **total weight of the electric propulsion system** is **4212,28 N (429,4 kg)**

So, the electric system weights a 40% more (161 kg more) than the fuel propulsion system. It is not a very significant weight, for instance between the own outboards can exist (50 kg mass differences) but in the hypothetical case that the weight might suppose a problem, the maximum weight charge allowed or the maximum number of occupants could be reduced.

7.5. Approximated autonomy of the electric propulsion system

Once the different basic components are chosen, an approximated calculation of the autonomy of the boat has been done. Thus, in this section the battery capacity (30 kWh) and the power consumption of the electric motor (equation 1 and graphic 1) have been related.

So, using this information the following graphic (graphic 3) has been calculated. It illustrates the autonomy in hours depending on the instantaneous speed. Given that the solar energy could be irregular or non-existent (at night for example), in all these autonomy calculous the provided energy by the solar panels has been dismissed.



***Graphic 3** Autonomy vs Speed*

When the graphic is analysed it can be observed that the power consumption (as it is showed in graphic 1) in low speeds is very low. As a consequence of this, the autonomy is very high in low speeds (more than 40 hours in speeds lower than 7 knots). When the boat is navigating at the higher speed (23 knots), it can be observed that the autonomy reduces to a value of 1,23 hours.

According to the tests made by touron-nautica (table 1), at a cruise speed of 15,9 knots, the equivalent fuel engine (Mercury 40) consumes 10,2 litters per hour which means that it has an autonomy of 4,9 hours. At this speed, our propulsion system has an autonomy of 3,72 hours which is lower but is a sufficient competitive autonomy.

8. Connection components and schema

8.1. DC/DC converter function

A DC/DC converter is an electronic circuit or electromechanical device that converts a source of direct current (DC) from one voltage level to another. It is a type of electric power converter.

DC/DC converters are usually used in EV vehicles. The most commonly used DC/DC converters in electric vehicles are the unidirectional converters and the bidirectional converters. On one hand, unidirectional converters typically cater to various on-board loads such as sensors, controls, safety and navigation equipments. These, are designed to move power in one direction, from dedicated input to output. However, bidirectional converters are able to move power in either direction. A typical application of bidirectional converters is in cars with a regenerative braking system. [17]

8.2. AC/DC rectifier function

A rectifier is a device for turning alternating current into direct current. Alternating current (AC) flows in both directions, switching back and forth many times every second. Direct current (DC) only flows in one direction.

The AC current first goes into a transformer. As shown in Fig. 32, the current through the primary coil create a moving magnetic field that induce current in the other. In step-up transformers, the voltage increases and in step-down transformers the voltage decreases.

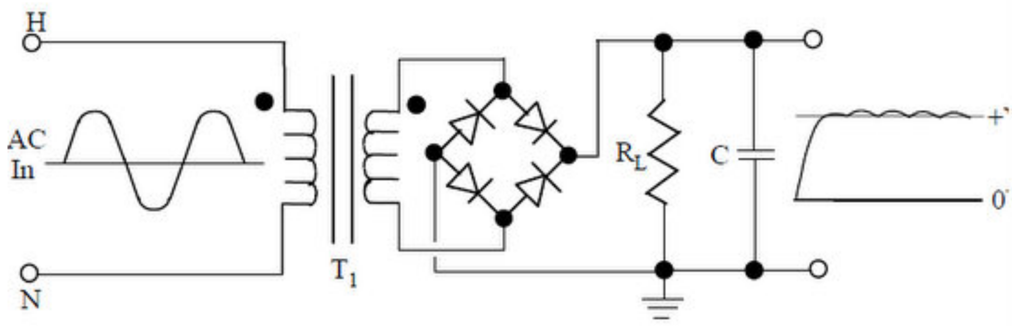


Fig. 32 *AC/DC rectifier functioning schema*

Then, the current goes to the diodes. Diodes let current flow in one direction and stops when the current tries to flow the other way. [18]

8.3. Maximum power point tracking (MPPT) controller

Maximum power point tracking (MPPT) is a technology used in photovoltaic modules to extract the maximum power. MPPT controllers have an efficiency up to 96%. Thus, to increase the efficiency of the solar panels it is necessary to mount a MPPT.

An MPPT controller function is similar to a car transmission. When the transmission is in the wrong gear, the maximum power is not transmitting to the wheels.

8.4. Connection schema for the system basic components

The components used in this system need to work in very different voltages. Therefore, the best way to realize all the connections between these components is not an easy task. In this thesis, the components will be connected to a “central network (350 V dc)”. This central voltage is not a random value, it is determined principally by the motor and the batteries voltage. The chosen components that have to be connected in this central network are:

- The solar panels (one panel):

MAXIMUM POWER	120 (W)
MAXIMUM VOLTAGE	20.88 (V)
MAXIMUM AMPERAGE	5.97(A)

- The battery:

NOMINAL VOLTAGE	375 (V)
CAPACITY	30 (kWh)

- The induction motor:

INPUT POWER	30 (kW)
NOMINAL VOLTAGE	345 (V)

First of all, the seven solar panels have been connected in parallel.

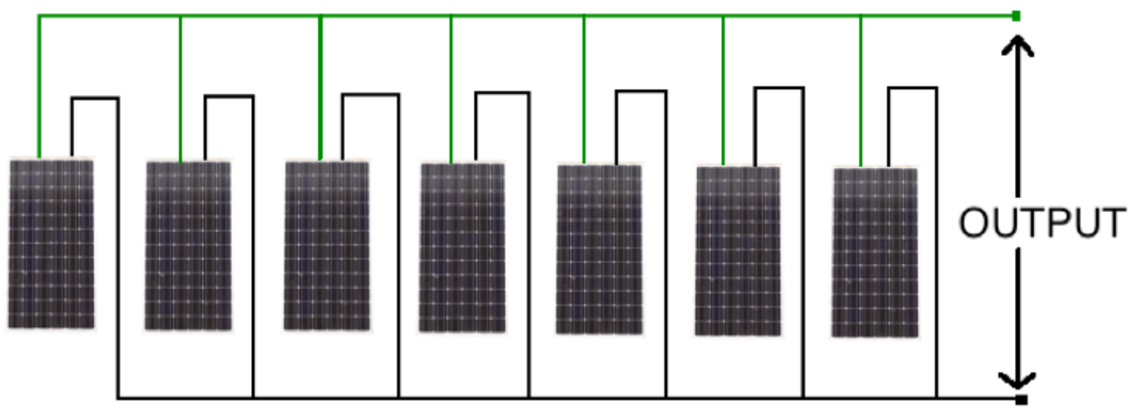


***Fig. 33** Solar panels connection schema*

Then, the final connection scheme is the following one (Fig. 34):

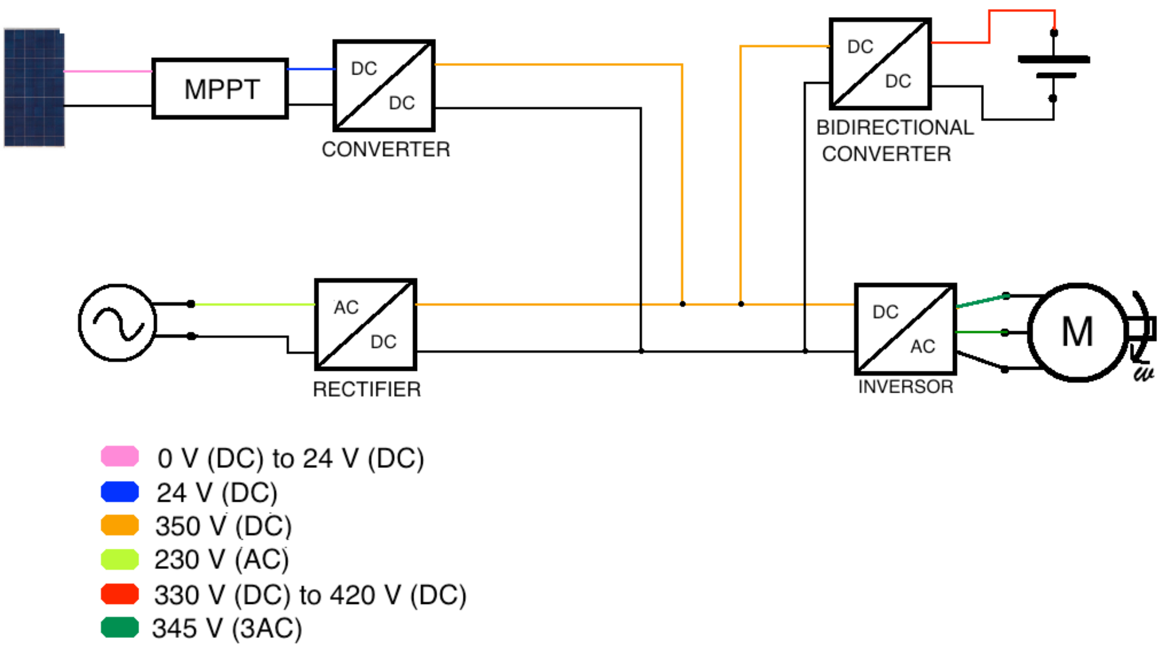


***Fig. 34** Components connection schema*

So, the solar panels are connected to a maximum power point tracking controller (MPPT), to extract the maximum power of the sun, and then to a DC/DC converter to increase the voltage to 350 V DC.

The batteries of the system are connected next to a DC/DC bidirectional converter. It allows the charge and the discharge of the battery. In this case, the Lithium-Ion battery has a nominal voltage of 375 V and given that it has 192 cells distributed in 8 modules (4 of them of 14 cells and 4 of 10 cells) the nominal voltage of each cell can be calculated. The result of this calculation is that the nominal voltage of each cell is 3,9 V. In 3,9 V Lithium-Ion cells the maximum charging voltage is 4,2 V thus the charging voltage must be approximately 420 V. In addition to this, the battery voltage will range from 330 V (in the discharged state) to 420 V (in the charged state).

Then, given that the chosen motor is a three-phase induction motor, a DC/3AC inversor is needed between the motor and the central network.

Finally, the system is connected to the electrical network using cetac plug. Cetac is an industrial connector, it works with the plugs that are placed in the most of ports.

To explain how the system works it is necessary to analyse the different working modes.

8.4.1. First working mode: Docked at the port

The first one is when the boat is docked at the port. In that case we can suppose that the electric motor is not working (OFF position), the boat is plugged in (by using cetac connector) and the solar panels are producing.

In these conditions, the scheme is (Fig. 35):

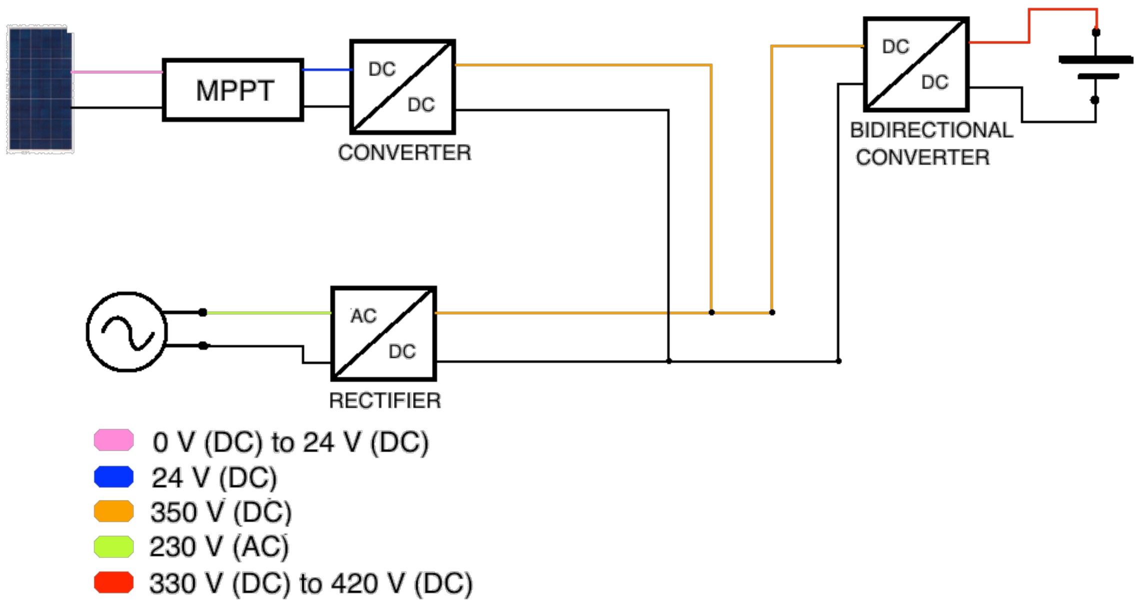


Fig. 35 *First working mode schema*

When the boat is docked at the port, the energy comes from the electrical network and from the sun at the same time. They charge the batteries.

8.4.2. Second working mode: Sailing

The second working mode considered is while the boat is sailing. When the boat is navigating, obviously cetac is unplugged and the motor is working (consuming electrical energy). In this conditions, the energy used by the motor comes from the battery and the solar panels.

Thus, in this case the connection scheme is (Fig. 36):

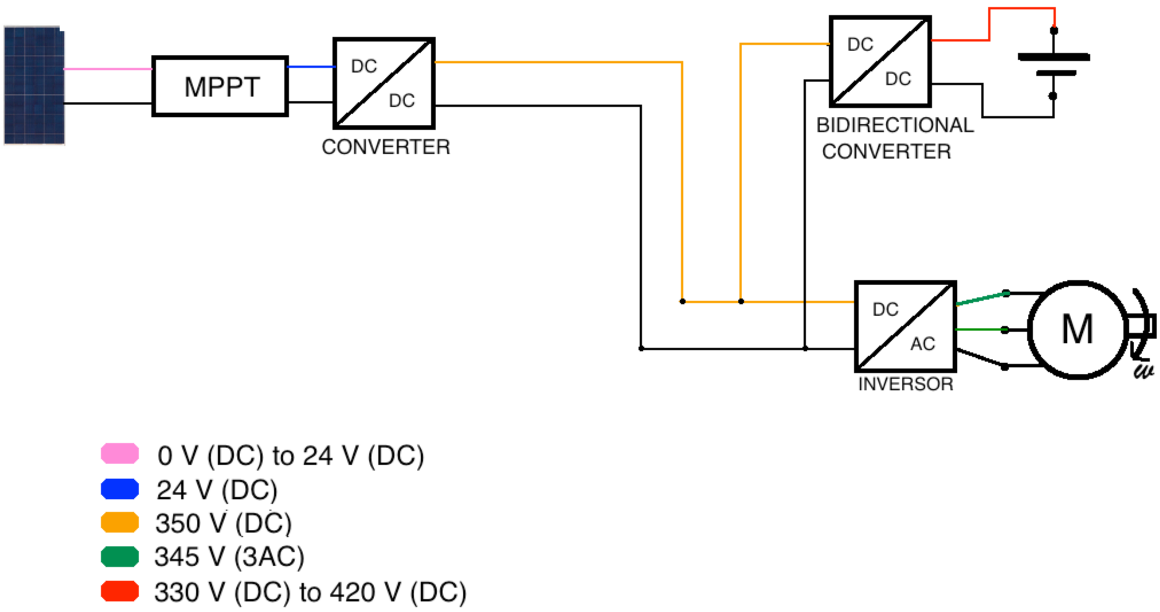


Fig. 36 *Second working mode schema*

8.4.3. Third working mode: Anchored

Basically, the idea in this third working mode is that the motor is disconnected and the cetac unplugged. This can happen for example while the boat is anchored (near the coast) or when the boat is docked at the port with the cetac unplugged.

Thus, in the third working mode the motor is not consuming energy and the energy obtained by the solar panels is stored directly in the batteries.

The connection scheme in these conditions is the following (Fig. 37):

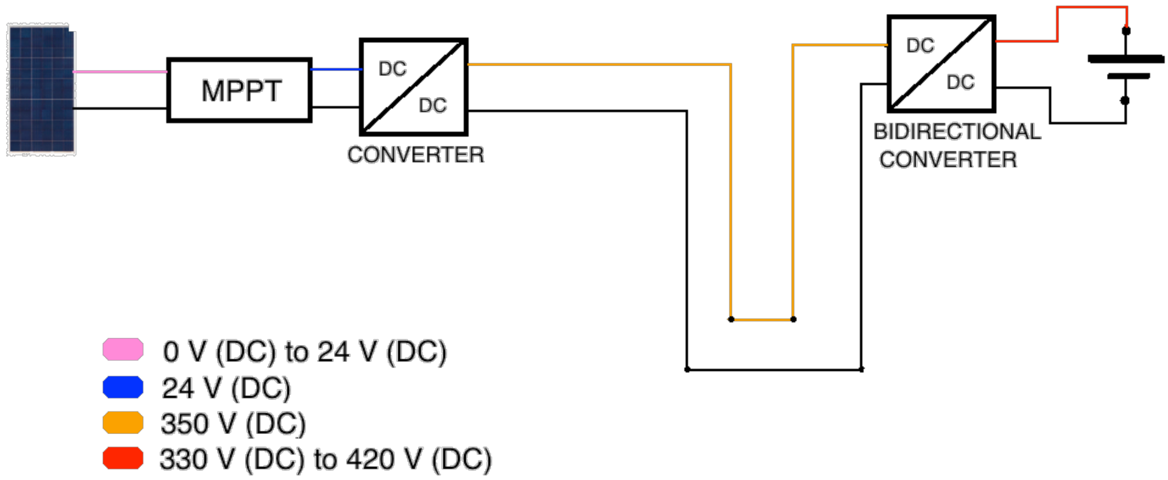


Fig. 37 *Third working mode schema*

8.5. Connection components

As it is explained in the chapter 7.4 and showed in the Fig.33, there are five connection components. Given that the system works in very specific and different voltages, the selection of the connection components has not been easy.

On the one hand, the maximum power point tracker (MPPT), that is situated next to the 7 solar panels (connected in parallel) should bear the maximum amperage, the maximum power and the maximum voltage (delivered by the solar panels). Finally, it has been chosen the Epsolar IT6415ND Maximum power point tracker which can work in 12/24/36/48 V and it supports a maximum amperage of 60 A. [19]

Fig. 38 *Epsolar IT6415ND*

On the other hand, the other connection components i.e the both DC/DC, the AC/DC and the DC/3AC are very specific and in a hypothetical prototype they should be specially done for it.

9. Hardtop design and FEM simulations

9.1. Hardtop design

One of the designed parts in this project is the hardtop. This design has been done using SolidWorks that is a CAD program. The basic function of the hardtop in our system is to increase the available area to place the solar panels.

A hardtop, as said previously, is a typical part in this kind of boats. In an open concept boat, the sun hits hard and in the middle of the sea it is necessary to find a shadow. So usually hardtops are used for casting a shadow on the boat. In the fishing version of this boats, normally the hardtop structure incorporates some complements or additional parts like supports for rods.

Fig. 39 *Traditional hardtop*

In our design, the intention is also casting a shadow but the difference is on the top of the hardtop. In that case instead of being covered using fabric this part is covered of solar panels. This solar panels let us leverage the solar energy to recharge the batteries and obviously casting a shadow on the boat.

The design of the hardtop has been conditioned by the dimension of the chosen solar panels and obviously the boat dimensions. All the anchors position is conditioned by the boat design. Then, to design the superior part of the hardtop, where the solar panels are placed, the solar panels size (1200mm x 540mm x 3mm) has been taken into account. Obviously, the intention is to collocate the maximum solar panels allowed by the boat dimensions. In this case, given the boat size, the maximum coherent surface for the superior zone of the hardtop is (2700mm x 1740mm). With this surface (4,698 m^2) seven solar panels can be placed.

Finally, the boat aspect with the hardtop is the following.

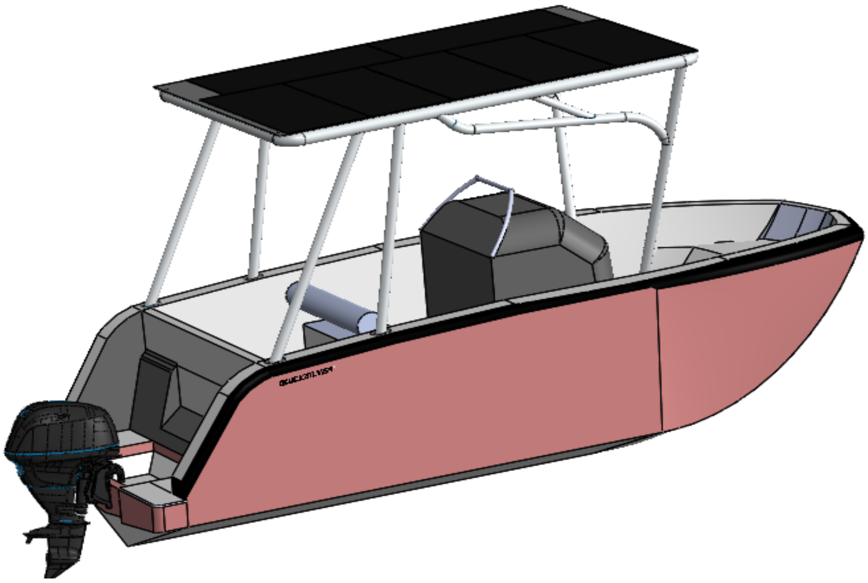


Fig. 40 *Activ 505 with the designed hardtop*

9.2. HARDTOP FEM SIMULATIONS:

Among this chapter, the simulations of the hardtop structure are shown and analysed. The intention of this simulations is validating the mechanical properties and prove that the hardtop structure is resistant.

During the usable life of the hardtop and the whole propulsion system, the components are exposed to the weather and the gravity conditions. These conditions could damage system components.

So, the effects of this conditions should be analysed specially for the hardtop. The hardtop incorporates the supports and the orientation system of the solar panels and it is subdued to several circumstances like the wind, the snow or the gravity. As a consequence of this conditions, some reactions appear to the hardtop structure.

Therefore, the studied conditions are:

- Solar panels weight.
- Snow conditions.
- Wind conditions
    - Boat maximum speed (≈23 knots).
    - High wind conditions.

To carry out this simulation ANSYS and ANSYS Workbench has been used. ANSYS is a finite element solver.

9.2.1. Hardtop CAD importing, meshing, material properties and boundary conditions:

To realize a correct simulation is very important to apply and reflect the different real forces and boundary conditions to the model.

This stress and deformations study has been done with the finite elements program Ansys Workbench. First of all, the hardtop CAD model has been designed (using SolidWorks) and has been imported (using the Ansys extension Design Modeller) to the FEM program prepared to be meshed and solved. When CAD is imported the first step is defining the material properties. Given that this hardtop has to be near the sea during the main time of its lifetime, a stainless steel has been chosen to build the structure.

Finally, it has been used the F-313 (UNE 36016) stanless steel. This steel has a very good resistance to corrosion, even in contact with electronegative metals. It has a high stress resistance and it has an easy mechanization.

The properties of the (F-313) stainless steel are: [24]

	F-313 PROPERTIES (UNE 36025)
Density (Kg/m^3)	8030
Young Modulus (GPa)	210
Poisson's ratio	0.3
Yield strength (MPa)	735,5 - 833,6
Braking strain (MPa)	882,6 – 980,6

Table 10 *F-313 properties*

The next step is meshing the structure applying all the material conditions. A 10 mm meshing has been applied to the model (14982 nodes).

Along all these simulations the weight of the mechanical part of the orientation system has been dismissed. This weight has been dismissed because forces caused for this are very small compared with the other boundary conditions applied to the model.

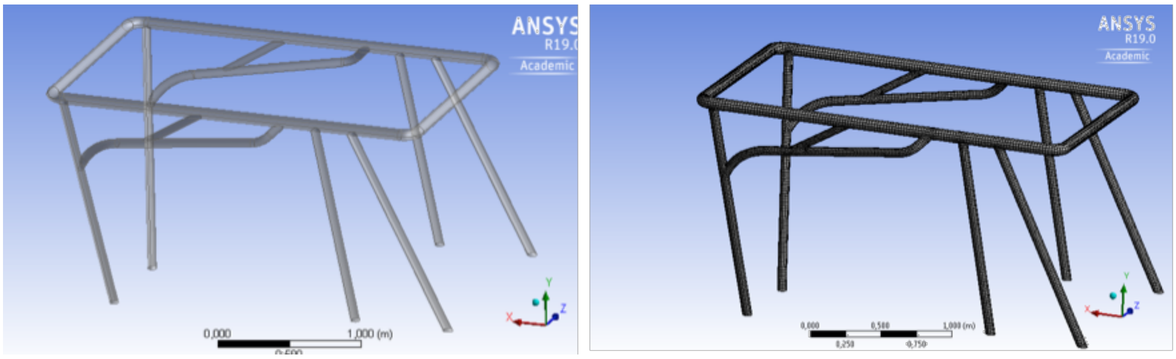


Fig. 41 (a) (b) *Hardtop meshing step*

Finally, the following boundary conditions has been applied to the meshed model.

- **Hardtop lineal motors reaction forces**

Given the conceptual design of the Solar Panels orientation system (explained in section 10) and analysing the reactions that the junctions cause to the hardtop we can identify that four linear forces appear on the top structure of the model.

The forces are intended to be applied in a linear distribution because the motor guide is subjected in the hardtop bar.

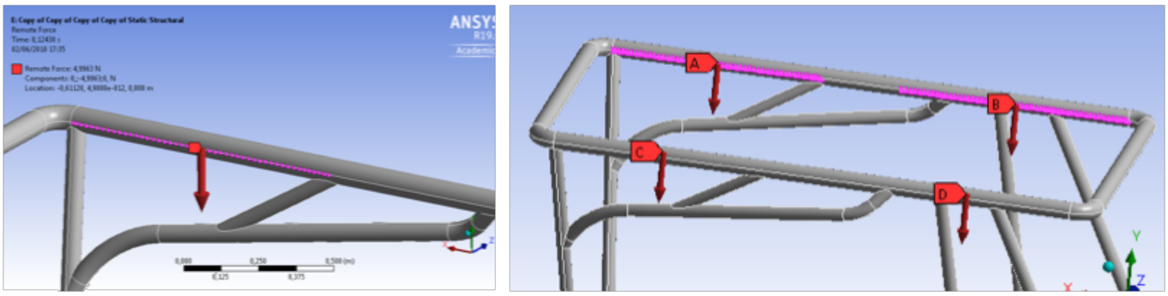


Fig. 42 *Boundary conditions of the motors reaction forces*

- **Hardtop fixations (anchors)**

This hardtop is fixed on the boat with six fixation points. To translate this in boundary conditions for our Ansys model it is very important to analyse how supports work. This imply the fixation of the lowest part of the steel tube. We can fix this part because its welded to the fixation plate. This plate is screwed to the boat. The number and the sizing of this screws should be proportional to the reaction forces studied then. Given that the structure is symmetric, in the symmetric loads cases, anchors reactions will be only studied in anchors 1, 2 and 3.

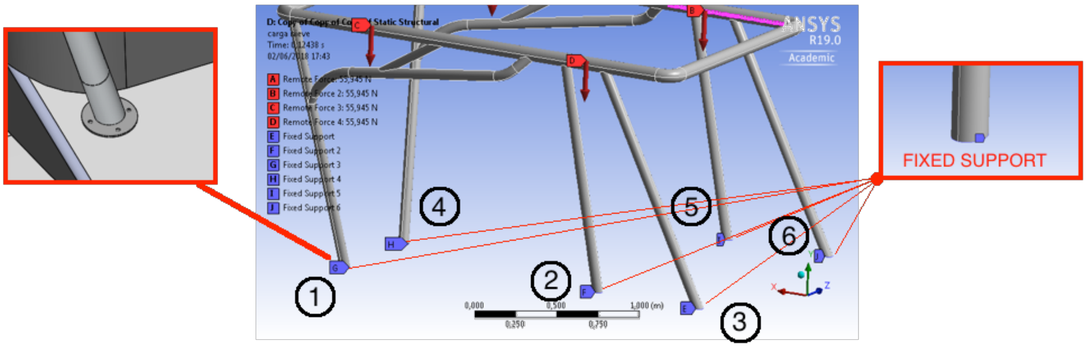


***Fig. 43** Boundary conditions of the hardtop fixations*

When all the model is meshed and the boundary conditions that has to be applied are known, we can proceed to the study of the cases. The difference between every case are the forces that are applied to the model.

Among all the analysis realized in this chapter, X axis direction coincide with the advance boat direction, Y axis is perpendicular to the boat floor and Z axis is the cross product between X and Y.

9.2.2. Solar panels weight:

As explained before the solar panel system consists in seven solar panels. Every one weights 22,96 N so the total system weights 160,68 N. Applying the gravity, the total force caused by the system to the hardtop structure is 160,68 N, as explained before, distributed in four forces.

$$F_{TOTAL} = \left(SolarModule_{weight} \times Numb.\right) \times g = (2{,}34 \times 7) \times 9{,}81 = 160{,}68$$

- *Displacement plot:*

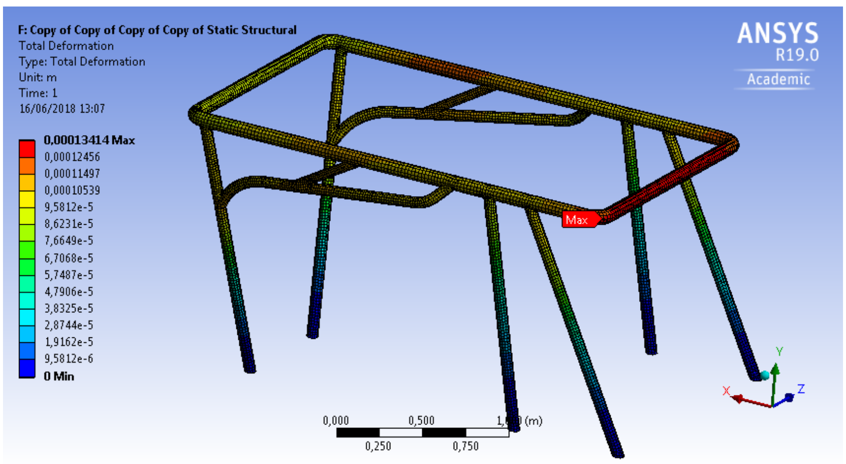


***Fig. 44** Displacement plot of the hardtop structure*

- *Stress plot*

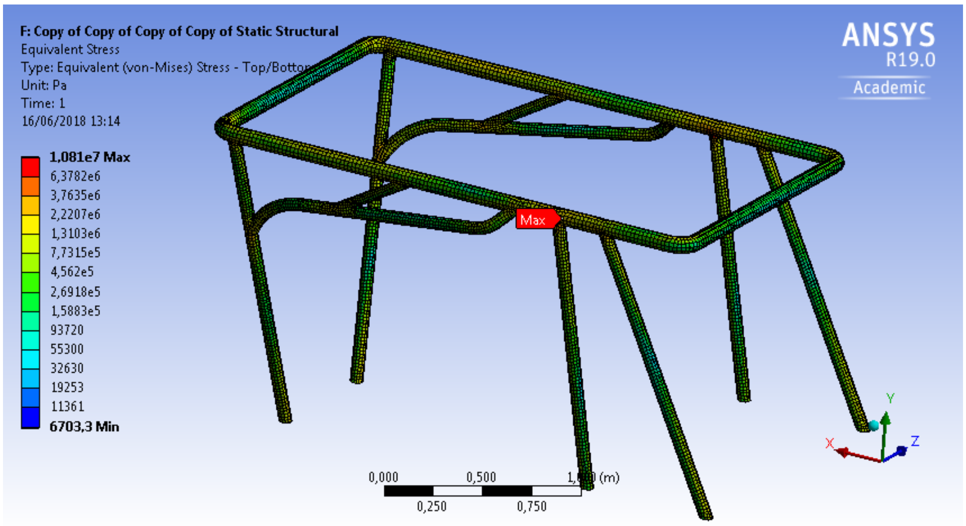


***Fig. 45** Stress distribution of the hardtop structure*

- Results analysis:

The maximum calculated displacement is in the rear part of the hardtop and it has a value of 0,134 mm.

In this case, the maximum (marked in the stress plot MAX) is not the maximum stress point, because in this junction a singularity can be observed. When this singularity is dismissed and the stress plot is properly analysed, it can be observed that the maximum stress value is 5,5 MPa.

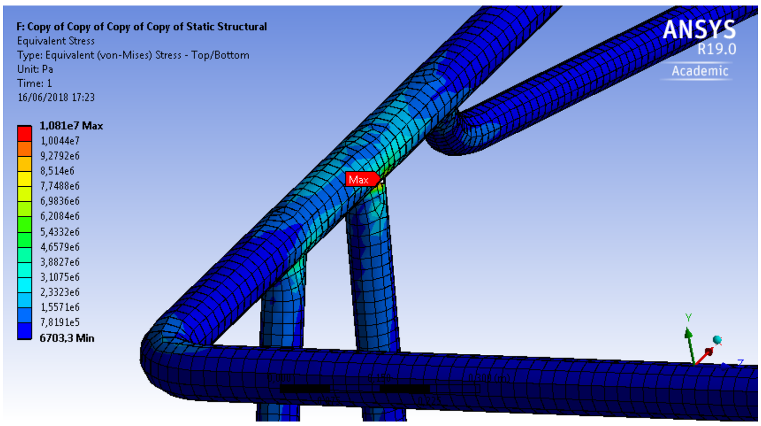


***Fig. 46** Detail of the singular point in the hardtop*

Obviously, all the stresses and deformations in this case of study are not very high. This is because the applied loads are very low. With these loads the safety factor is very huge, so it has not been calculated.

- *Anchors force reaction analysis:*

ANCHOR NUMBER	*F_X (N)*	*F_Y (N)*	*F_Z (N)*
1	-1,34	30,36	-7,7178
2	8,759	56,281	0,346
3	-7,421	-6,462	0,426

Table 11 *Anchors reaction forces*

9.2.3. Snow conditions

According to the normative NBE-AE/88 the overload caused by the snow to a horizontal surface in a topographic altitude from 0 m to 200 m is of 40 kg/m^2.

Finally, the total weight that the structure has to support is the snow weight 1638 N (167 Kg) and the solar panels weight 160,68 N (16,38 Kg).

It is important to detach that this analysis is very similar with the previous one. The difference is that in this one higher weight forces are applied to the model.

So, the four forces applied to the structure are of -449,8 N

$$F_{TOTAL} = (Snow_{Weight} + SPanels_{Weight}) \times g = 1799{,}2\ N$$

- *Displacement plot:*

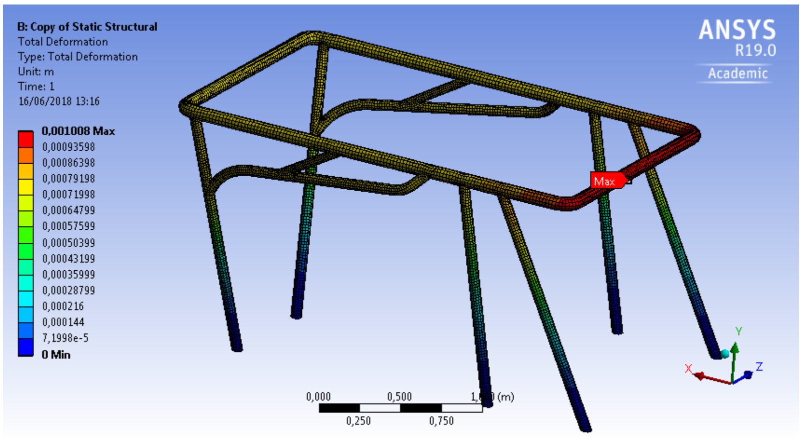


Fig. 47 *Displacement plot of the hardtop structure*

- *Stress plot:*

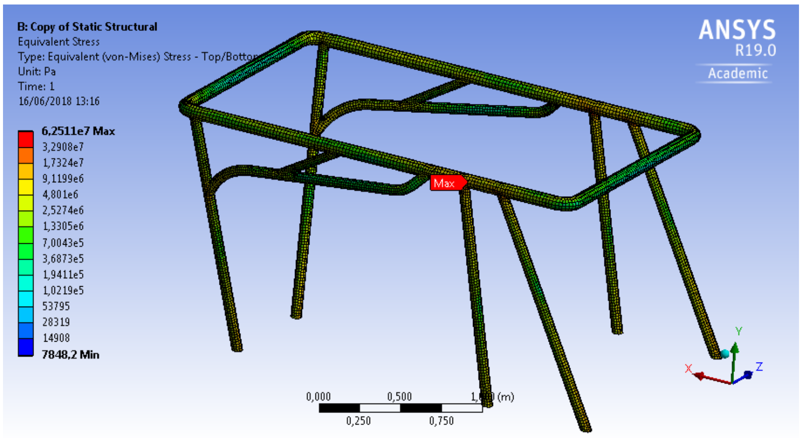


Fig. 48 *Stress distribution of the hardtop structure*

- *Results analysis:*

As we can see in the displacement plot, the maximum displacement is in the rear part. The displacement in this zone has a value of 1 mm, which means that the hardtop structure has a very low displacement if a snow overload occurs to our system.

When the Von-Misses stress is analysed, we can observe (like the previous case) that there is a singular point. When all the affected nodes are dismissed, the maximum stress value is 52,02 MPa.

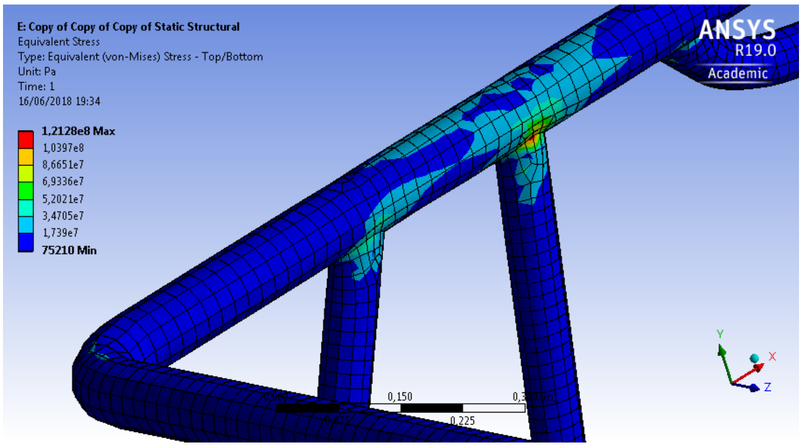


Fig. 49 *Detail of the singular point in the hardtop*

Finally, it is possible to calculate the safety factor:

$$\gamma = \frac{\sigma_y}{\sigma_{MAX}} = \frac{735{,}5\ MPa}{52{,}02\ MPa} = 14{,}13$$

- Anchors force reaction analysis:

ANCHOR NUMBER	*F_X(N)*	*F_Y(N)*	*F_Z(N)*
1	-15,051	340,63	-86,592
2	98,27	631,46	3,889
3	-83,269	-72,502	4,776

***Table 12** Anchors reaction forces*

9.2.4. Wind conditions

In this part the effects of the wind are studied. First of all, the effects and forces caused by de wind on the solar panels surface has to be simulated. Once the wind forces have been found the next is applying them to the meshed model to perform the simulation.

To study the wind effects, some factors like the panels orientation, wind direction, wind speed and boat speed have been taken into account.

In wind simulations showed below these factors have been applied in the most harmful way to present the most extreme cases.

- **Case 1: Boat maximum speed and forward inclined (no wind assumed)**

In this first case wind is not assumed. When the boat is sailing at the maximum speed, approximately 23 knots (42,6 km/h), with the hardtop inclined at the maximum tilt (25 degrees) against the wind.

- Air flow simulation (23 knots ≈ 42,6 km/h):

The purpose of this simulation is calculating the forces caused by the wind while the boat is sailing at the maximum speed.

The force results (assuming Y axis up and Z axis parallel with the boat direction) in the solar panels structure are:

- FX = 200,48 N
- FY = 427,8 N
- FZ ≈ 0 N

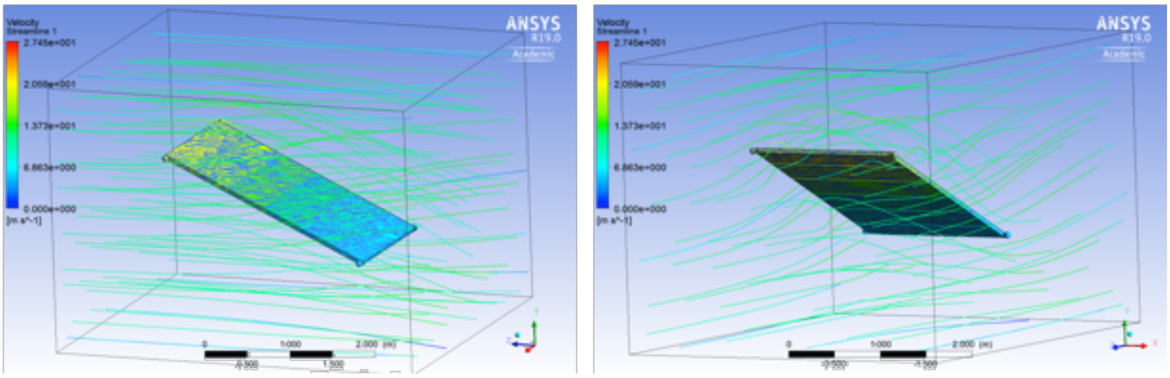


Fig. 50 *Fluent air flow simulation*

After that, boundary conditions (forces) have been applied using fluent results and the model has been solved by using the finite elements method. Then, the displacement plot and the Von-Misses stress plot have been calculated.

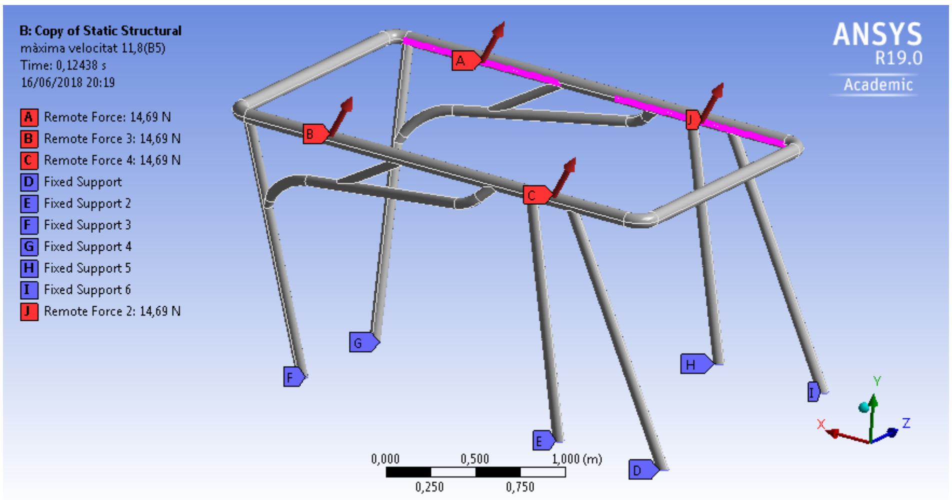


Fig. 51 *Boundary conditions of the motors reaction forces*

- *Displacement plot:*

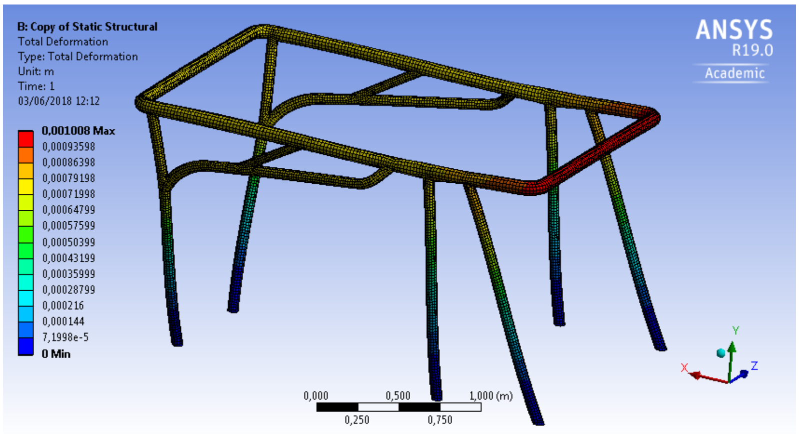


Fig. 52 *Displacement plot of the hardtop structure*

- *Stress results:*

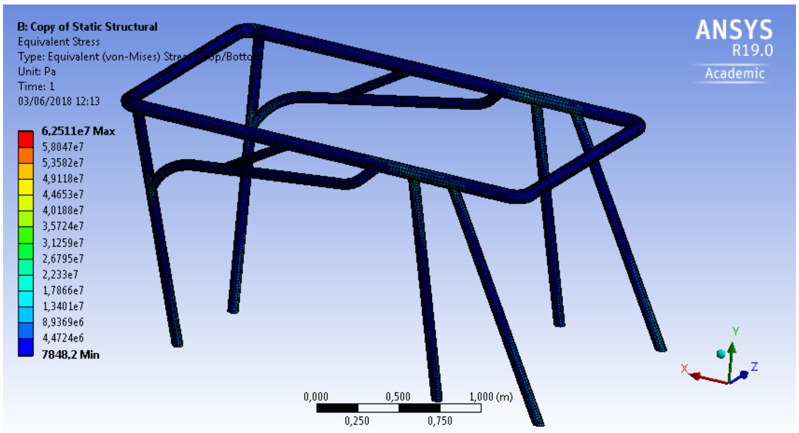


Fig. 53 *Stress distribution of the hardtop structure*

- *Results analysis:*

In this case, the maximum deformations are given in the rear part of the hardtop (red zone in the Deformation results plot. The deformation in this zone (in absolute value) is 0,001008 meters.

Moreover, when Von-Misses stress results are analysed, a singular point is detected. So, the maximum tension in the structure with this boundary conditions is 31,26 MPa.

$$\gamma = \frac{\sigma_y}{\sigma_{MAX}} = \frac{735{,}5\ MPa}{31{,}26\ MPa} = 23{,}52$$

- *Anchors reactions:*

ANCHOR NUMBER	*F_X(N)*	*F_Y(N)*	*F_Z(N)*
1	20,682	-84,879	21,67
2	-29,989	-279,75	-1,369
3	109,56	150,75	-1,220

***Table 13** Anchors reaction forces*

- **Case 2: Lateral gust of wind**

In this case of study a lateral gust of wind has been applied to the solar panels structure. The wind speed considered has been 100 km/h and the solar panels structure is inclined lateral sidelong forming a tilt of 44 degrees (maximum lateral tilt) with the horizontal.

- <u>Air flow simulation (100 km/h):</u>

As the previous case, the affected part (in this case solar panels structure) has been simulated by using fluent to find the forces caused by the wind at a speed of 100 km/h.

In this case the wind force results in the solar panels structure are:

- FX ≈ 0 N
- FY = 4410 N
- FZ = 3916 N

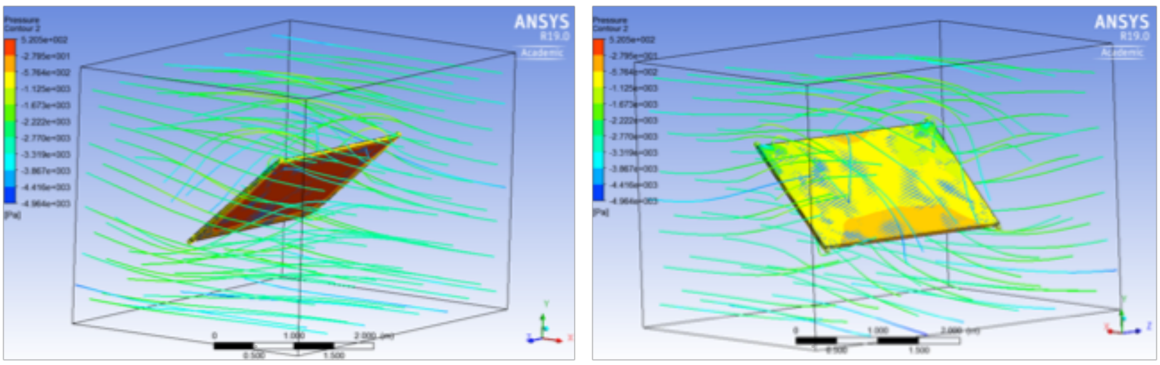


***Fig. 54** Fluent air flow simulation*

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As in the other cases, the boundary conditions (forces) have to be updated using the fluent results and the model has to be solved by using the finite elements method.

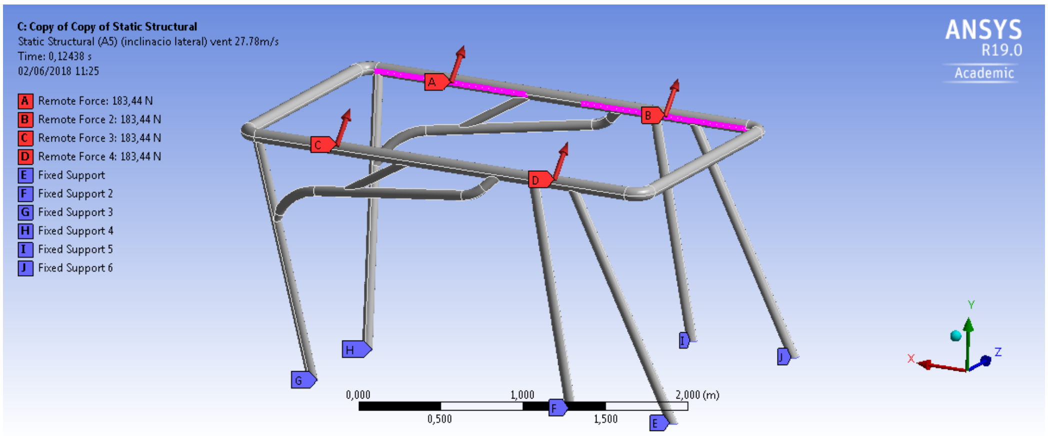


Fig. 55 *Boundary conditions of the motors reaction forces*

After solving the system, the deformation plot and the stress plot have been obtained.

- *Displacement plot:*

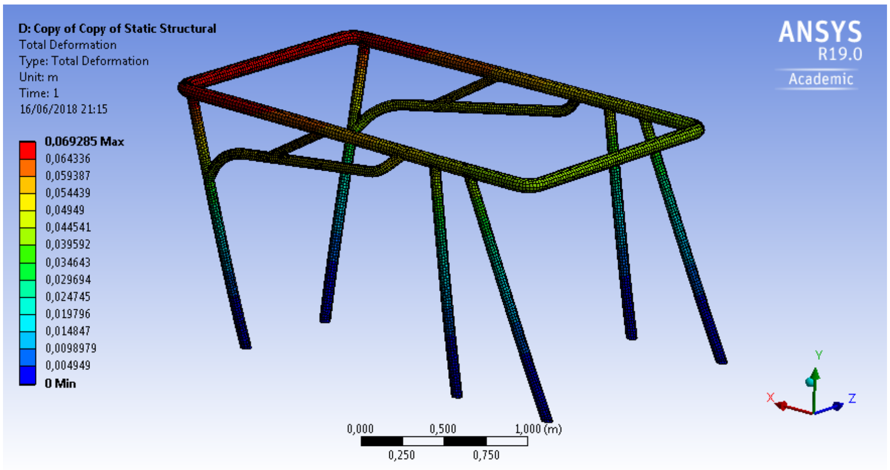


Fig. 56 *Displacement plot of the hardtop structure*

- *Stress results:*

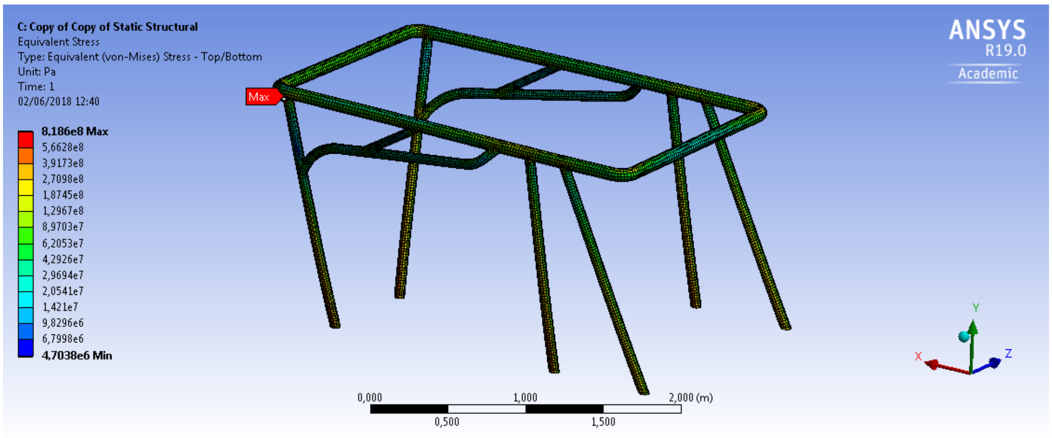


Fig. 57 *Stress distribution of the hardtop structure*

- *Results analysis:*

As we can see in the deformation plot, the maximum displacement is in the top, left and frontal part of the hardtop structure. It has a value of 6,92 cm.

When these results are analysed we can observe that the maximum Stress value is $8.186 \cdot 10^8$ Pa. But when we approach to the maximum stress zone we can see that it is a singular point which means that we have to assume this singularity to realize the analysis. Finally, if we dismiss these affected nodes the maximum stress value is 295 MPa.

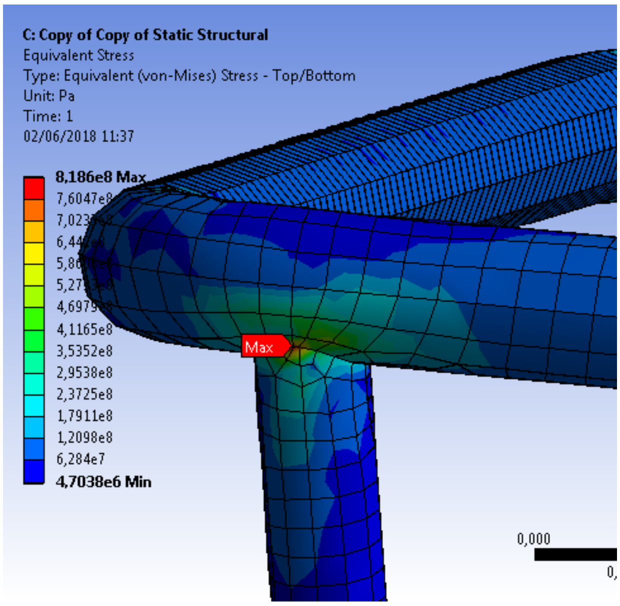


Fig. 58 *Detail of the singular point in the hardtop*

The safety factor has a value of:

$$\gamma = \frac{\sigma_y}{\sigma_{MAX}} = \frac{735{,}5\ MPa}{295\ MPa} = 2{,}49$$

- *Anchors reactions:*

ANCHOR NUMBER	*F_X(N)*	*F_Y(N)*	*F_Z(N)*
1	-149,29	-590,41	-578,22
2	-570,56	-3075,8	-673,23
3	3651,33	1031,6	1324,4
4	215,36	-1086,4	-1003,4
5	84,384	-46,643	653,42
6	-231,23	-643,06	-494,18

***Table 14** Anchors reaction forces*

- **Case 3: Frontal gust of wind + maximum boat speed (forward inclined)**

As in the first case, the effects of the wind when the boat is sailing at the maximum speed has been studied. The difference is that in this case of study it has been considered a frontal gust of wind (100 km/h).

So, a wind speed of 142,6 km/h has been applied to the model.

- Air flow simulation (142,6 km/h):

As in the previous cases (case 1 and case 2), the solar modules support structure has been simulated to find the forces caused by the wind.

Thus, the wind forces are:

- FX = 2094 N
- FY = 4401 N

- FZ ≈ 0 N

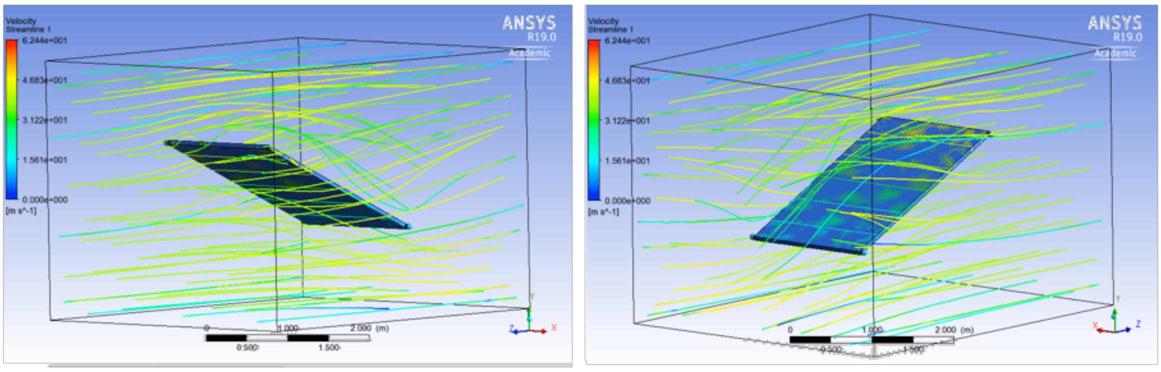


Fig. 59 *Fluent air flow simulation*

As in the other cases, the boundary conditions (forces) have to be updated using the fluent results and the model has to be solved by using the finite elements method.

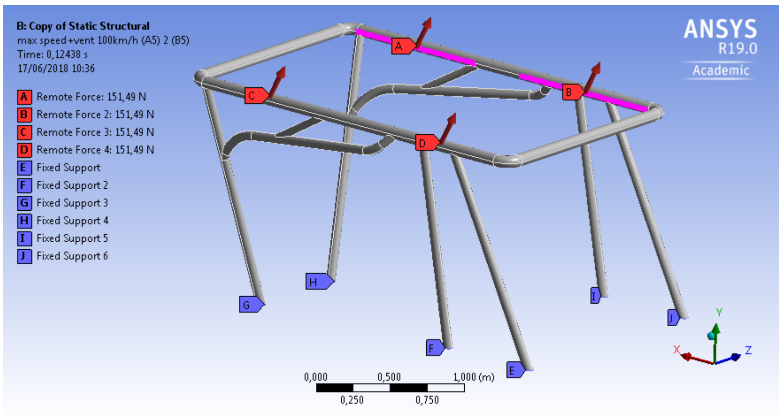


Fig. 60 *Boundary conditions of the motors reaction forces*

Then, the system has been solved and the displacement plot and the Von-Misses stress plot have been obtained.

- *Displacement plot:*

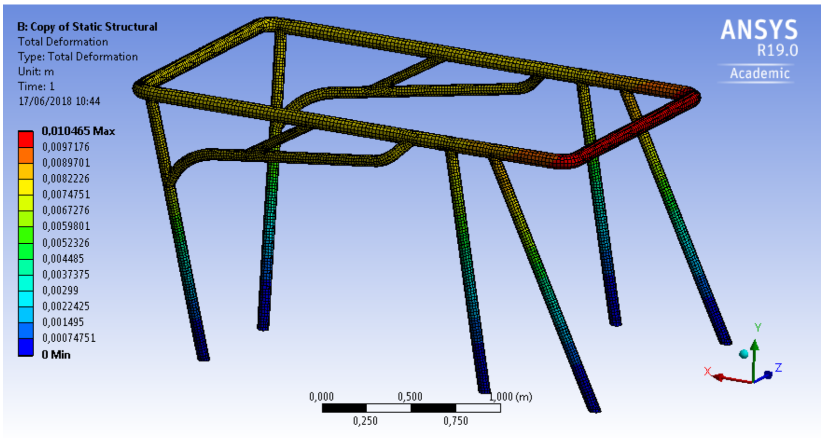


Fig. 61 *Displacement plot of the hardtop structure*

- *Stress results:*

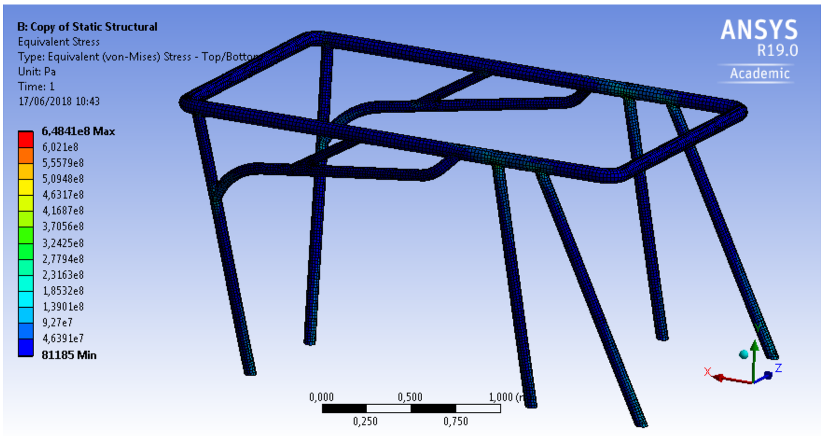


Fig. 62 *Stress distribution of the hardtop structure*

- *Results analysis:*

Like occurs in the first case, the maximum deformation is in the superior and rear part of the hardtop. It has a maximum value of 10.47 mm.

When the Von-Misses stress plot is analysed, there is a singular point. If these nodes are discarded, we can assure that the maximum stress value is 370 Mpa.

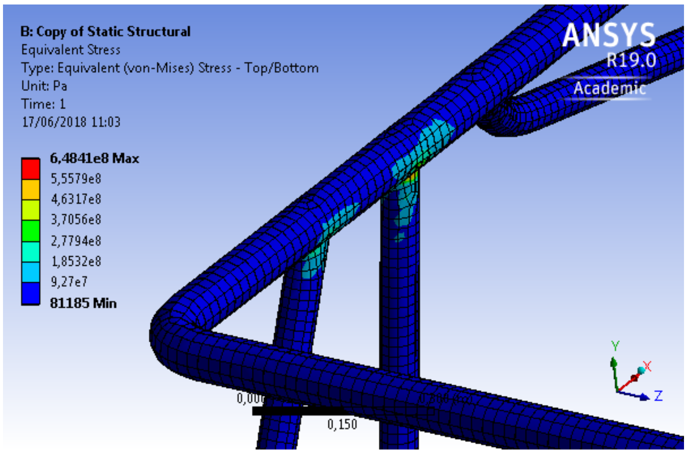


Fig. 63 *Detail of the singular point in the hardtop*

Thus, the safety factor is:

$$\gamma = \frac{\sigma_y}{\sigma_{MAX}} = \frac{735{,}5\ MPa}{370\ MPa} = 1{,}98$$

- *Anchors reactions:*

ANCHOR NUMBER	$F_X(N)$	$F_Y(N)$	$F_Z(N)$
1	215,28	-873,58	223,04
2	-309,43	-2896,7	-14,147
3	1140,3	1570,4	-12,561
4	207,96	-880,46	-222,58
5	-320,17	-2925,8	13,453
6	1158,1	1606,1	12,795

Table 15 *Anchors reaction forces*

- **Case 4: Rear gust of wind**

In this case of study, the effects of a rear gust of wind (100 km/h) on the solar panels structure have been simulated. We have considered that the solar panels structure is tilt (rear part up) at the maximum angle (30 degrees).

The fluent simulation is the same it was in the first case but now the longitudinal forces are in the opposite direction.

Thus, the forces are:

- FX ≈ 0 N
- FY = 4410 N
- FZ = 3916 N

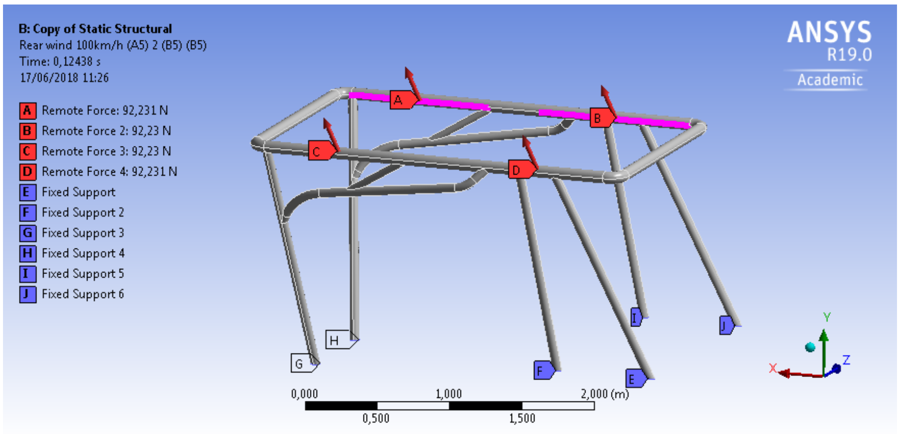


Fig. 64 *Boundary conditions of the motors reaction forces*

After solving the system, the deformation plot and the stress plot have been obtained.

- *Displacement plot:*

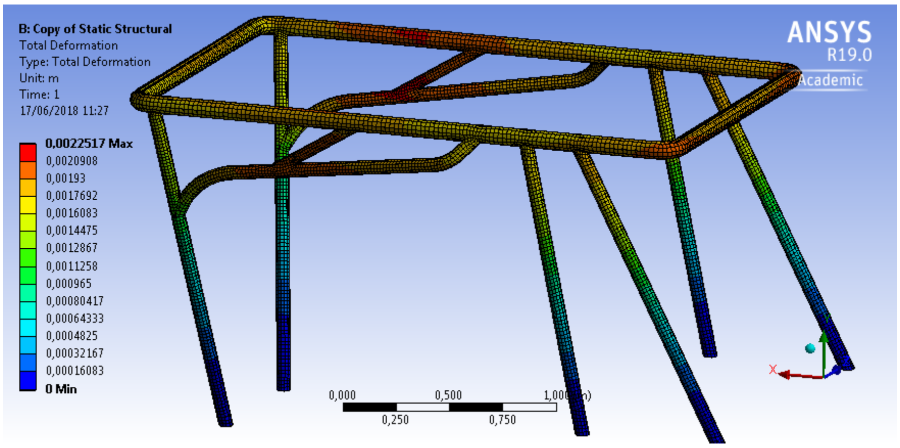


Fig. 65 *Displacement plot of the hardtop structure*

- *Stress results:*

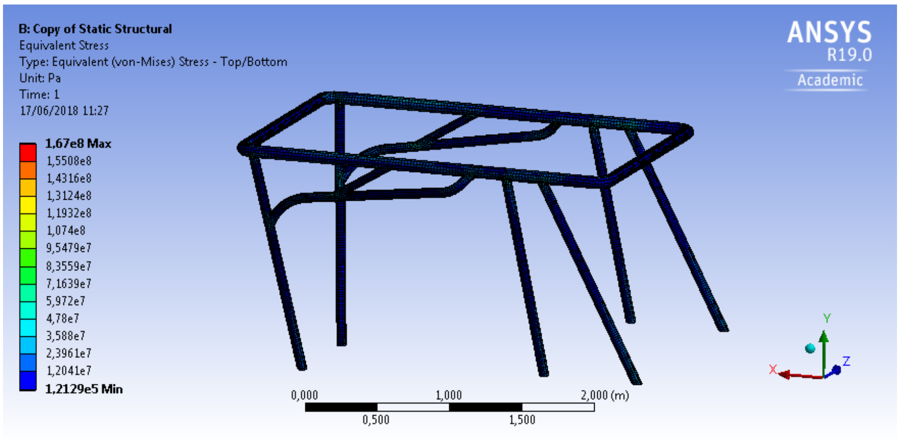


Fig. 66 *Stress distribution of the hardtop structure*

- *Results analysis:*

The maximum displacement is in the central part of the structure and it has a value of 2,25 mm. It is a very low displacement.

In the Von-Misses stress study there is a singular point. Dismissing this singular point the maximum stress value is 107 MPa.

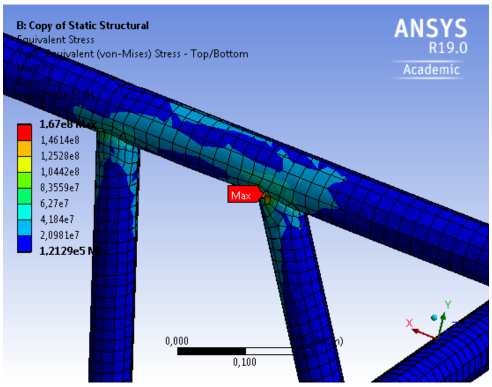


Fig. 67 *Detail of the singular point in the hardtop*

Thus, the safety factor in this case has a value of:

$$\gamma = \frac{\sigma_y}{\sigma_{MAX}} = \frac{735{,}5\ MPa}{107\ MPa} = 6{,}87$$

- *Anchors reactions:*

ANCHOR NUMBER	$F_X(N)$	$F_Y(N)$	$F_Z(N)$
1	-85,535	-483,32	122,28
2	-104,73	-123,25	-2,98
3	-442,52	-734,76	-6,58
4	-86,88	-490,38	-122,88
5	-109,27	-133,75	3,828
6	-436,73	-717,08	6,33

Table 16 *Anchors reaction forces*

9.3. Screw sizing

Screw sizing is a very important thing to be analysed. The screws are the responsible to fix the hardtop structure with the boat. If the screws are undersized, they could break. If this happened, the structure could fall down.

To size the screws, it is important to know how fixations work. As it is showed in Fig. 68, the hardtop structure supports in six circular supports. Moreover, in this chapter it will be determined how many screws should be in every anchor.

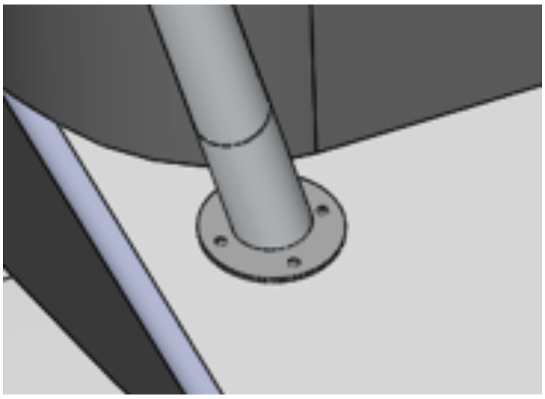


Fig. 68 *Anchor detail*

To define the number of the screws and the dimension of them, the maximum anchors reactions (found in the previous simulations) have to be analysed.

All the screws can support a yield and a traction force. In the analysed cases, it can be observed that the reaction forces appeared in every anchor have the both components.

Type	High resistance screws	
Class	8.8	10.9
f_{ub} (N/mm^2)	640	900

***Table 17** High resistance screws f_{ub}*

Using these properties, the calculation forces (yield and traction) have to be obtained.

On one hand, the yield resistance force ($F_{yield,t}$) is:

$$F_{yield,t} = \frac{0.5 \cdot f_{ub} \cdot A_s}{\gamma}$$

***Equation 4** Yield resistance force*

$f_{ub} = Traction\ resistance\ of\ the\ screw\ (^{N}/_{mm^2}).$

$\gamma = Partial\ security\ coefficient = 1{,}25$

$A_s = Resistant\ area\ of\ the\ shank.$

On the other hand, the traction resistance force ($F_{traction,t}$) is:

$$F_{traction,t} = \frac{f_{ub} \cdot A_s}{\gamma}$$

***Equation 5** Traction resistance force*

But sometimes the screws are submitted to a traction force and a yield force at the same time. When these occurs, the next expression must be accomplished (to guarantee the screw resistance). [21]

$$\frac{F_{yield,screw}}{F_{yield,t}} + \frac{F_{traction,screw}}{1{,}4 \cdot F_{traction,t}} \leq 1$$

***Equation 6** Simultaneous traction force and yield force condition*

In all the simulations, the reaction forces in the anchors have been calculated. Then, the yield force (that it is the resultant of x and z axis forces) and the traction force (total) supported by the four screws located in the anchors have been obtained and analysed.

It is important to distinguish that the yield forces are supported and distributed by the static friction forces of the contact surface and the screws. Given that the friction forces depend of the normal force in every case the friction forces have to be recalculated.

$$F_{Friction} = \mu \cdot N$$

***Equation 7** Friction force*

$\mu = 0{,}3 = Friction\ coefficient\ between\ the\ contact\ surfaces.$

$N = Normal\ force\ (N) = Weight \cdot 9{,}81 + F_y + F_{screw} \cdot n.of screws$

$F_{screw} = Compresion\ force\ of\ the\ screw$

Finally, if the chosen screws are M82 (10.9 class), its properties are: [22]

D	5 (mm)
A_s	36,368 (mm^2)
Generated force	22,751 (N)
f_{ub} (N/mm^2)	900
$F_{traction,t}$	26.184 (N)
$F_{yield,t}$	13.092 (N)

***Table 18** M8 (10.9 class) properties*

With this parameters, it has been calculated the yield and the traction forces that have to be supported by the screws ($F_{traction,screw}$, $F_{yield, screw}$).

In the first calculation, it has been assumed a total of 4 screws in each anchor:

Number of screws	4
Maximum $F_{traction,screw}$	24,36 (N)
Maximum $F_{yield\ screw}$	886,83 (N)
Maximum combined forces	791,7 (N) traction force
	444,48 (N) yield force

Table 19 *Forces results with 4 screws*

As it can be observed, the maximum yield force and the maximum traction force are not higher than the maximum allowed for the screws. Equation 6 is also accomplished.

The maximum pure traction force is given in the maximum speed with the solar panels forward inclined simulation in the central anchors. The maximum yield force (pure) is given in the third anchor in the lateral gust of wind simulation. Finally, the maximum combined force (yield and traction at the same time) is given in the second anchor also in the lateral gust of wind simulation.

Thus, the final decision is to screw the anchors to the boat with four M8 screws (10.9 class).

10. Solar panels orientation system:

The intention of this system is to orientate the solar panels to increase the vision factor between the sun and the solar panels. The orientation system has been designed in a conceptual way.

To achieve this, the hardtop is intended to be equipped with a mechanical system controlled by an electronical system. This system gives two degrees of freedom to the solar panels (pitch and row) see in Fig. 73 and Fig. 74

10.1. Electronic system components

For what it does to the electronic part of the inclination system. It consists in three basic elements working all together:

- Inclinometer.
- GPS.
- Microcontroller.

In this case, the microcontroller is the responsible to control the different mechanical system motors and brakes coordinately with the information given by the GPS and the inclinometer.

An electronic inclinometer is a device used to measure angles with a high precision. Electronic inclinometers use an internal gyroscope. This gyroscope stays in one position, independently of the orientation. To calculate the angle of the object, the inclinometer compares this angle to the gyroscope. Mercury inclinometers work in the same way but instead of using a gyroscope they use mercury liquid. The inclinometer intention is testing the solar panels surface tilt constantly through time. At the same time a GPS is giving the boat coordinates and the boat orientation to the microcontroller.

All this information is constantly analysed by the microcontroller. This microcontroller calculates the optimum tilt and using this live data (pitch, row and coordinates) gives the orders to the different motors to execute the inclination.

To calculate the optimum solar panel angle, the microcontroller has to take into account three factors:

- The latitude (position of the boat).
- The month of the year.
- The direction of the boat.

If the boat is placed in the northern hemisphere, solar panels should be pointed due south. If the boat is placed in the southern hemisphere, solar panels should be pointed due north. Thus, the microcontroller gives lateral inclination when the boat is orientated in the range from NE to SE and from SW to NW or in the other cases (from NW to NE or from SW to SE) it gives the orders to incline the solar panels surface frontally or backward.

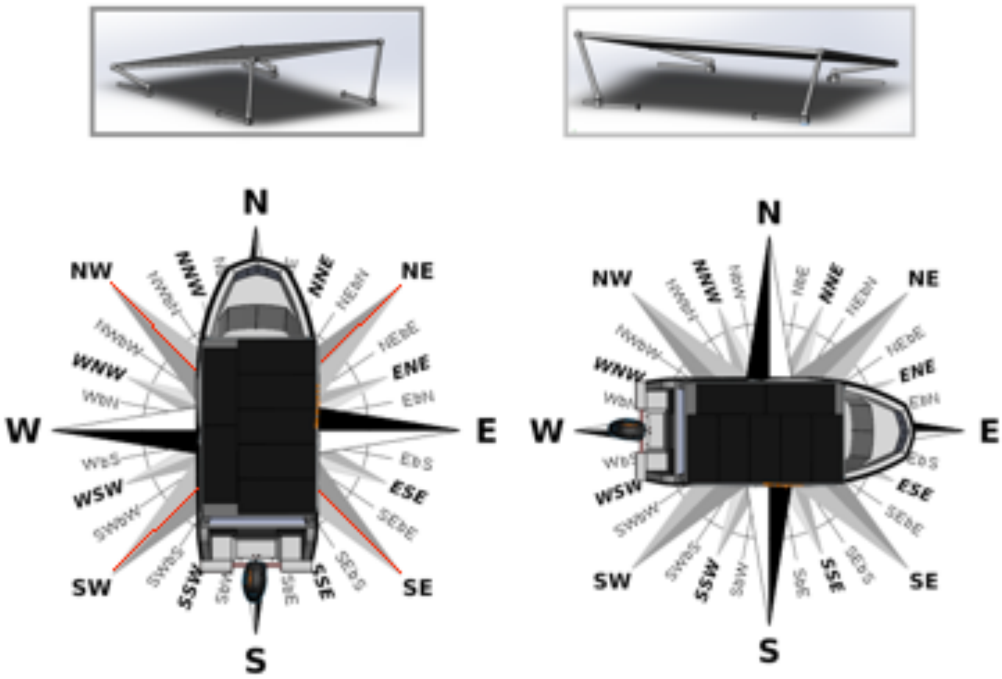


***Fig. 69** Inclination modes*

The latitude is a geographic coordinate that specifies the north-south position of a point on the earth surface. The latitude and the season of the year are the parameters that determine the tilt angle.

Thus, solar panels optimum tilt is calculated with three different equations: [23]

First equation (for winter):

$$Tilt\ (degrees) = (Latitude \cdot 0.9) + 29$$

***Equation 8** Winter tilt*

Second equation (for summer):

$$Tilt\ (degrees) = (Latitude \cdot 0.9) - 23.5$$

***Equation 9** Summer tilt*

<u>Third equation (spring and fall):</u>

$$Tilt\ (degrees) = Latitude - 2.5$$

Equation 10 *Spring and fall tilt*

10.2. Mechanical system conceptual design

This mechanism has some design requirements:

- It is intended to be as integrated as possible. The design is meant to be the similar as possible as a traditional hardtop. A thick design could be visually unaccepted by a possible costumer.
- It has to supply to the solar panels surface at least 2 degrees of freedom.

Basically, the mechanical part of the tracking system is composed by four brakes, four motorized linear guides and four linear motors. The solar panels surface is articulated in the four extremes. This part is connected with the mechanical system through a ball journal.

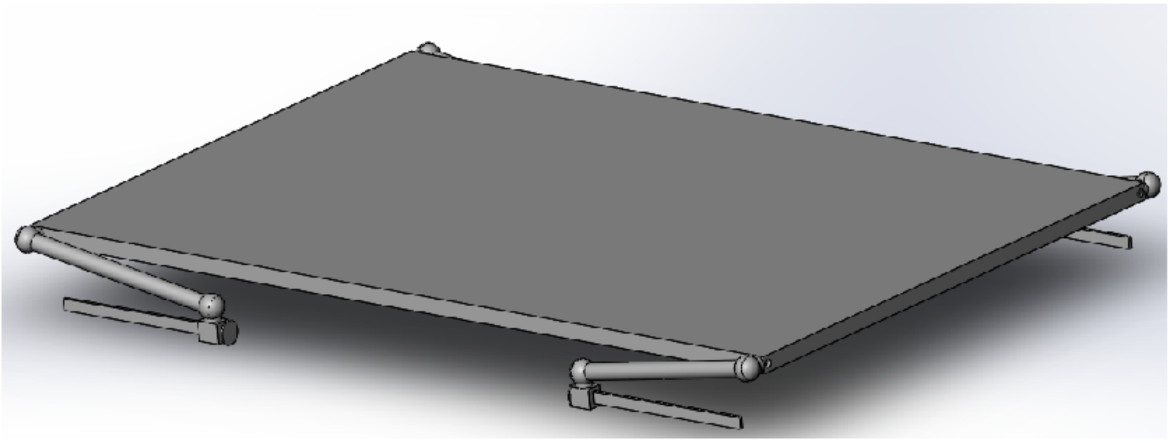


Fig. 70 *Orientation system*

The four "arms" objective is elevating the solar panels surface. Each "arm" has three basic parts:

1. A lineal motor.
2. A motorized linear guide.
3. An electronically controlled brake

These three components are connected as it is showed in the following image (Fig. 71).

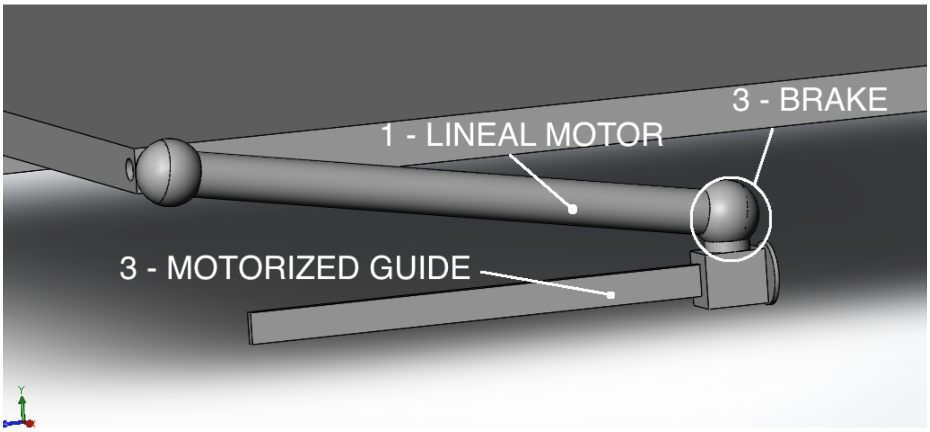


Fig. 71 *Orientation system parts*

These components are designed to work coordinately. When the system needs to raise up one side of the solar panels structure, it blocks the brake, the motorized guide and the lineal motor of the opposite side. Then, the first move (in the "arm" of the side that the system wants to rise up) is done by the motorized guide, that moves from the minimum position to the maximum position or the desired position to form the optimum angle. The lineal motor is usually in the minimum length positon but when the motorized guide is in the maximum length position, if the system wants to give a higher tilt to the solar modules, this lineal motor gives an extra tilt (to the structure) extending its length to the necessary value.

The intention of the brake is to control the angle (red angle in Fig. 72) between the lineal motor and the horizontal plane. When the break is unacted the connection moves like a ball journal.

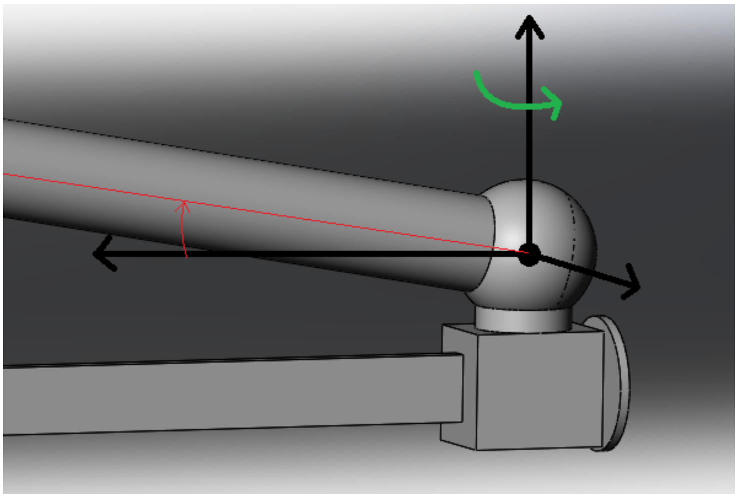


Fig. 72 *Detail and explanation of the orientation system*

10.2.1. Maximum tilt

In this case the maximum tilt depends on the inclination type. The system can give two inclinations to the solar panels surface:

- If the system is giving a lateral inclination to the solar panels the maximum tilt (without elongating the lineal motors) is 44 degrees and it is of 90 degrees when the lineal motors are in the largest position. The lineal motors are the part 1 in the Fig. 71.

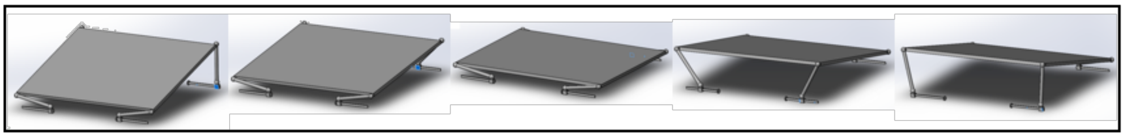


Fig. 73 *Lateral inclination of the conceptual orientation system*

- When the system is giving a frontal inclination, the maximum tilt without elongating the lineal motors is 25 degrees and then is 58 degrees after elongating the lineal motors.

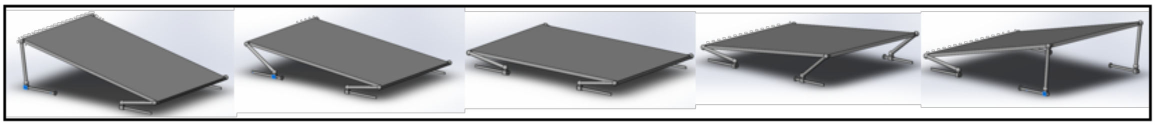


Fig. 74 *Frontal inclination of the conceptual orientation system*

10.2.2. Future improvements and steps of the mechanical system design

Given that in this thesis it only has been done the conceptual design of the solar panels inclination system there are many improvements.

- Make the system capable of carry out the both movements at the same time. This would improve the capability of increasing the vision factor between the solar panels and the sun giving the solar panels efficiencies up to a 100%.
- Design the support structure for the solar panels. This should be prepared to integrate all the cables and to work together with the other components.
- Choose all the definitive system components.
- Add some aerodynamic elements to make the system (and in turn the boat) more aerodynamic. This upgrade could be very useful when the boat is navigating and the solar panels are tilted.

11. Budget

The intention of this section is determining a rough guess of the development cost of the project. Given that this is a Bachelor Thesis, any salary has been earned by the student. Obviously, in real life this labour hours are paid. Thus, to carry out an approximation of the development cost the first step is making an estimation of the hours spent in each part. Then, the approximate fees of the engineer per hour have been supposed. These fees are variable depending on the part made by the engineer.

In this project, the amount of 300 hours has been spent. This number of hours is not a random value. It has been considered that the project has a value of 12 ECTS credits. Every credit involves approximately 25 hours of work.

If the project work is divided in parts:

	Cost (€/h)	*Hours (h)*	*(€)*
Research	100	30	3000
Documentation	20	25	500
Conceptual designs (Hardtop, conceptual solar panels inclination system)	100	75	7500
Hardtop FEM analysis	100	50	5000
CAD designs	35	60	2.100
Electrical connections	50	60	3.000
TOTAL			**21.100**

So, the project has a total cost of 21.100 €.

12. Environmental impact

Every day, the society is more aware about carbon footprint. Specially, with the increasing problem of global warming, customers and companies around the world are changing their mind. A clear example of this, is the automobile industry. Nowadays, automobile industry is adapting to these new necessities and new customers taking out new eco-friendly models.

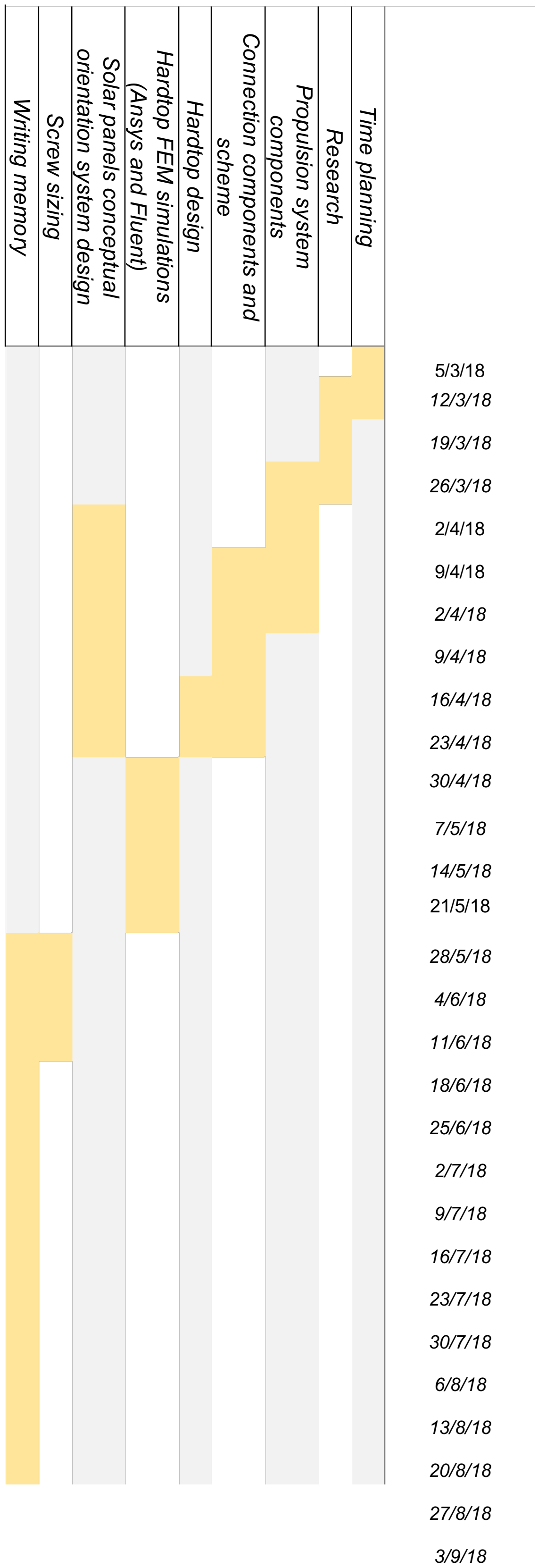
In an ideal future, all the electric energy should be obtained through renewable energies. To achieve this, some countries particularly in Europe, are approving new laws and launching awareness campaigns. Unfortunately, these days not the whole electric energy produced comes from clean sources. Thus, it cannot be strictly said that the design is a zero-emissions propulsion system.

When the recyclability of the system pieces is analysed. We can observe that the majority of the materials of the solar panels are recyclables but actually the recycling systems are not advanced enough. So, solar panels recycling industry will have a high economical potential next years. But clearly the piece that could be more problematic after its lifetime is the battery. These batteries contain environment-dangerous materials that could not be recycled.

In the case of the designed hardtop, it is recyclable because it is made of steel. In fact, steel is one of the world’s most recycled material and its properties remain untouched after being recycled.

Given that the proposed propulsion system (in contrast with the fuel based propulsion systems) is a zero emissions propulsion, in the future it is of interest a quantitative calculation of the carbon footprint.

13. Time planning



14. Conclusions

With the aim to propose an electric propulsion system with a better autonomous electric range, this project aims to **select and connect all the propulsion system components** and **design a hardtop equipped with solar panels** by considering the adequate inclination to provide the propulsion system with clean energy.

The **main components** of the electric propulsion system have been selected and a **connection proposal has also been done**. Some of the **connection components** have to be specially done for the designed system which is one of the weaknesses of the thesis.

ANSYS Workbench has been used to **validate the designed hardtop** (created with Solidworks) under different conditions such as wind, snow and weight. In this thesis, the most critical conditions for the designed hardtop simulated in ANSYS are assumed to be the ones that has the lowest safety coefficient. Based on the results, this corresponds to the one with the hardtop forwarded-up and a frontal gust of wind of 100km/h. In this situation, the safety coefficient is of 1.98 which is 58% greater than the general minimum acceptable (i.e. 1.25). Therefore, the designed hardtop fulfils the required demands.

The **solar panels orientation system** is designed such as that can be moved in the roll and pitch axes. Due to the limited range of movement of such orientation system, it is of interest in the future to expand such concept (detail design stage) and to evaluate if other possible movement ranges are viable.

Later, **a boat model equipped with the designed hardtop** is also presented. Since the hardtop parameters (e.g. dimensions) depend on the type of boat to be used, *Quicksilver Activ 505* is the open boat model used for this purpose. To do so, different components (i.e. the motor, the batteries and the solar panels) forming the electric propulsion system have been chosen based on the chosen boat model. In addition, the electrical network connection between all the components has been designed.

The proposed electric propulsion system with hardtop can be installed in any boat of an approximate range from 4,5 meters to 6,5 meters with few changes in the hardtop structure. After selecting the boat components, a **weight comparison** has been done and it has been concluded that the extra 160 kg should not be a problem for our project.

In the future, it is of interest to analyse in greater detail how to design such hardtop in a way that it is adaptable to a wider range of boats. Since the chosen electrical network connection components are not common in this thesis, a detailed economic analysis of the completed propulsion system including the hardtop should be carried out for large scale production scenario. Moreover, some future improvements as some aerodynamic elements, the design of a structure for the solar panels or the higher movement capability could be made to the orientation system (that in this thesis has been designed in a conceptual way). Lastly, it would be of interest to design the different components (e.g. motor and batteries) to obtain product specifications that can greater fulfil the market demands.

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